ALUMINIUM IN COMMERCIAL VEHICLES MANUAL

Joining – this document supersedes Chapter VIII & IX from the Manual dated August 2011

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Optimum exploitation of lightweight aluminium designs includes the application of large, integrated aluminium components, i.e. thin-walled castings, extrusion with sophisticated cross sections and single-piece sheet deep drawings. Consequently, the number and length of the required structural and non-structural joints can be reduced significantly. Nevertheless, there is still a need for consistent and reliable joining techniques for all-aluminium structures as well as mixed material designs (i.e. joints between aluminium and steel, magnesium, plastic and composite materials).

The various aluminium alloys and product forms can be joined using the techniques conventionally applied for steel, although some adjustments of the processing parameters may be required. But the specific characteristics of aluminium alloys also led to the development and application of new joining methods.

Fabricated products must be suitable for their intended use and manufacturers must prove that they show the required performance characteristics. Consequently, the selection of the applicable joining method is primarily determined by technical considerations. A most important factor is also the envisaged production volume. Furthermore, depending on the specific application, appropriate international design and manufacturing standards may have to be met. Thus, the choice of the optimum joining solution is a complicated task influenced by many different parameters.

A comprehensive description of the applicable joining methods for the fabrication and repair of aluminium structures can be found in the Aluminium Automotive Manual (http://www.european-aluminium.eu/aam/). In the following, a short summary of the most relevant techniques will be given.

Detailed information for direct application to specific technical projects may be obtained from the suppliers of aluminium semis and finished products as well as from the suppliers of joining equipment and additives. For additional information, reference is made to the literature, professional societies and other institutions, e.g. DVS (German Welding Society) (https://www.die-verbindungs-spezialisten.de), TWI (The Welding Institute) (http://www.theweldinginstitute.com), IIW (International Institute of Welding) (http://www.iiwelding.org), etc.
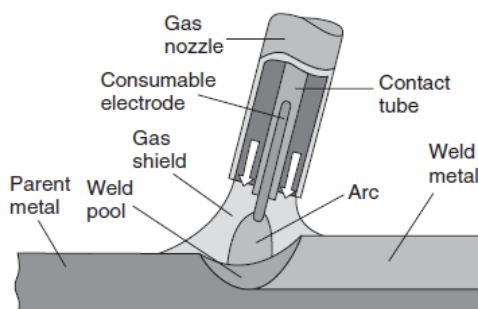
1. Welding

Welding is a joining process where the joint is accomplished by partial melting of the work pieces to form a pool of molten material that solidifies and establishes – after subsequent cooling – a firm, permanent connection. A filler material is sometimes added.

1.1 Arc welding processes

In arc welding, the welding heat is generated by an electric arc between a non-consumable, refractory (TIG welding and plasma welding) or consumable electrode (MIG welding) and the work piece. The weld area is shielded from the atmosphere by an inert gas.

### 1.1.1 MIG (Metal Inert Gas) welding

Fundamental features of the MIG welding process
(Source: Fronius)

In MIG welding, the electrode is an aluminium alloy wire which serves at the same time as the filler material. The welding wire uncoils automatically from a reel to the welding torch. A direct current power supply is used to create and maintain the electric arc. The shielding gas is normally argon; in special cases, argon-helium mixtures with small traces of oxygen are used.

The connection of the electrode to the positive pole ensures good oxide film removal, efficient heat transfer into the weld pool and a high deposition rate of the filler metal. Weld penetration and welding speed are high and the heat affected zone is narrow. In general, MIG welding calls for little post-weld finishing. But the high heat input in smooth current MIG welding has disadvantages. Welding of thin gauge aluminium (< 3 mm) is difficult and butt welds can only be produced using a backing bar, either integrated into the shape of the aluminium component or as a temporary removable feature. Thus, MIG welding methods offering lower heat input by appropriate current control are generally preferred as they also reduce thermal distortion of the welded assemblies.

*MIG welding with reduced heat input*

In pulsed current MIG welding, a stable arc which just preheats the surface of the work piece is maintained at a low background current whereas superimposed high current pulses detach and transfer single aluminium droplets from the electrode to the weld pool. Consequently, thinner material (> 1 - 2 mm) can be welded and butt welds up to 5 mm thickness can be produced without backing bar. Modern welding sets permit the use of a wide range of pulse amplitudes, durations and waveforms at frequencies from a few Hertz to a few hundred Hertz. Once the welding parameters are optimised, there is no spatter, gap bridging is improved and the small weld pool allows to weld in all positions.
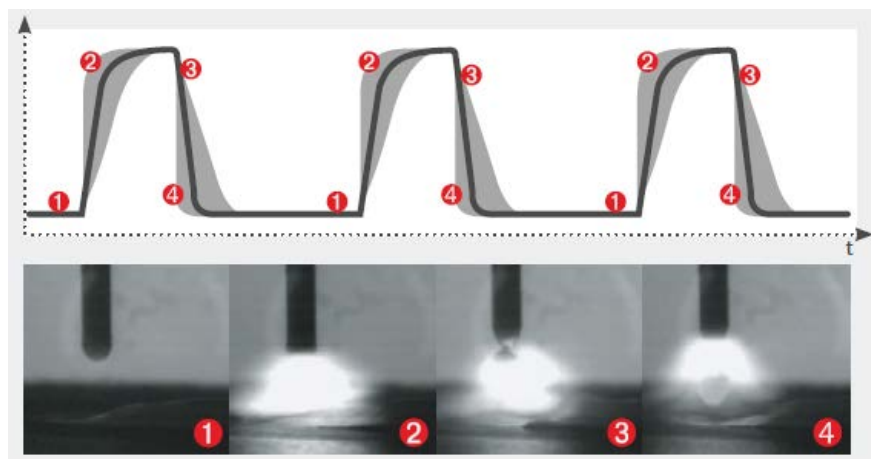
Pulsed MIG arc welding features a controlled material transfer

(Source: Fronius)

The other possibility is controlled short-circuit transfer MIG welding. At low welding currents, the tip of the continuously fed wire does not melt sufficiently fast to maintain the arc, but dips into the weld pool creating a short circuit. Molten metal transfer is governed by appropriate control of the current and/or wire feeding. Different methods are commercially applied. An example is the Fronius CMT® (Cold Metal Transfer) process which combines current waveform control with a pulsing wire feed technology. Since material transfer takes place with barely any current flow and very low heat input, even light-gauge aluminium sheets (0.3 - 0.8 mm) can be welded with high weld seam quality. Both methods are suitable for manual as well as automatic (robotic) welding.
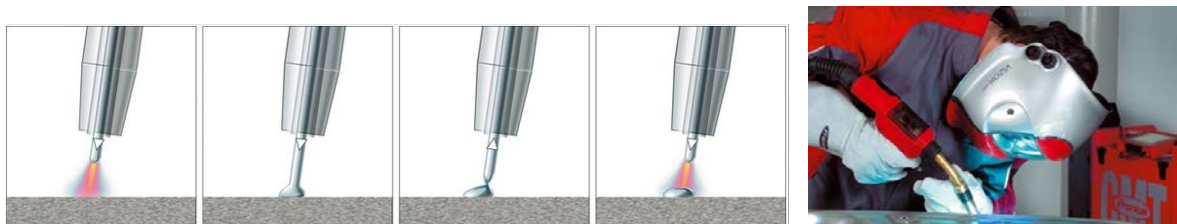

Reciprocating wire feeding in the CMT® (Cold Metal Transfer) welding process

(Source: Fronius)

High-performance MIG welding

High-performance MIG welding techniques aim to significantly increase the welding speed. A limited increase of the filer wire deposition rate can be achieved with a flat strip wire. For higher deposition rates, tandem MIG welding systems which have two separate wire feed units and two power sources are used. Electric insulation of the two electrodes offers versatile possibilities because the two wires can be controlled independently. The arc type (standard or pulsed arc) can be selected separately and also controlled short-circuit metal transfer processes can be integrated into the system. However, tandem MIG welding is only suitable for mechanised or robotic welding.
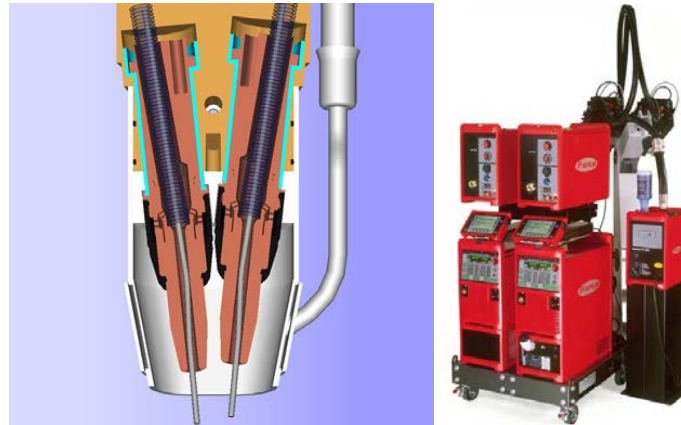

Tandem MIG welding system

(Source: Fronius)

For highest performance, MIG welding is combined with other welding techniques. Relevant for practical application are the Laser MIG welding process (see section 1.2.3) and the Plasma MIG welding process (see section 1.1.3).

1.1.2   TIG (Tungsten Inert Gas) welding

The TIG welding process uses a non-consumable, temperature-resistant tungsten electrode. Addition of a filler material is normally required to guarantee the metallurgical and mechanical properties of the joint. The filler wire is added separately to the weld pool, either manually or with a wire feed unit.

The standard shielding gas for aluminium TIG welding is argon as it optimises arc ignition and offers calm and stable metal transfer. Helium raises the arc temperature, leading to higher heat input into the work piece that can be exploited either to weld thicker materials or to increase welding speed. The use of argon-helium mixtures offers a compromise.
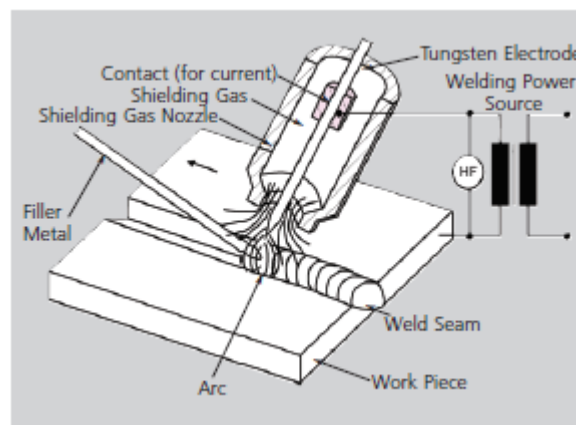
Principles of the TIG welding process

TIG welding is suitable for manual and automatic (robotic) welding. In many applications, it has been replaced by MIG welding, primarily because of the increased welding speed when welding thicker sections. However, TIG welding is still widely used since the small, intense arc provided by the pointed electrode is ideal for high quality,

precision welding. It results in a smooth weld bead with little undercut and no need for post weld finishing. Thus, it is often the preferred welding technique for visible joints.

TIG welding modes

Initially applied to all material thicknesses and joint types, TIG welding is today generally limited to join thin aluminium parts with thicknesses up to 6 - 10 mm. Normally, a high-frequency stabilized alternating current (AC) power source is used. The aluminium oxide film is removed during the negative phase, while the positive phase ensures penetration and cooling of the electrode. Full penetration welds can be made without backing bar. The welding speed is lower than for MIG welding and, for work pieces thicker than about 6 mm, preheating is required. The slow welding speed is also responsible for a wider heat affected zone and greater geometrical distortions.

Direct current (DC) power is only employed for specific applications. Welding with negative electrode (DC-EN) results in relatively deep and narrow weld penetration, and very little, if any, surface cleaning. Typically used with pure helium as shielding gas, this variant is capable of welding material thicknesses up to 25 mm. Properly pre-cleaned work piece surfaces are required; nevertheless, there is still an increased risk of welding defects. Because of the short arc length, only automatic welding is recommended. When welding with positive electrode (DC-EP), arc cleaning is excellent, but weld penetration is shallow. Only applicable for very thin gauge materials, this is the least used TIG welding method as it places a heavy thermal load on the tungsten electrode.

Square wave ("pulsed") and frequency controlled TIG (AC) welding

The difficulty of TIG (AC) welding is that the arc frequently extinguishes when the current reverses direction. In the past, a short high frequency spark of several thousand volts has been applied at the beginning of the positive and negative half cycles to encourage arc ignition; but the high frequency power source represents a potential hazard to any sensitive electronic equipment in the surrounding.
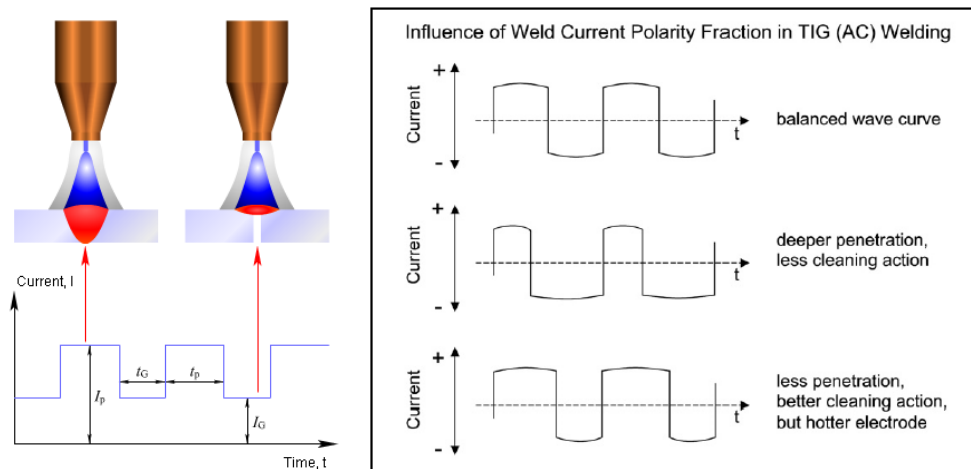
Pulsating square wave AC welding

The pulsating square wave technology eliminates the tendency for arc extinction by making the transition very quickly. During the high current pulse, the heat generated in the welding area leads to the fusion of work piece and, if applicable, filler wire. The low background current maintains the arc to avoid interruptions and ignition difficulties, but transmits only little heat into the work piece, i.e. the weld pool stays comparatively cool.

With proper selection of pulse times and current values, welding performance can be optimized, weld drop-through can be prevented and the weld seam appearance is improved. Increasing the time in EN mode effectively reduces the excessive etching zone beyond the toes or edges of the weld. Likewise, the time spent in EP mode is reduced and heat concentration on the tungsten electrode is lowered. The preferred range for aluminium work pieces is 68-75 % EN.

Advanced square wave techniques use modern inverter power sources providing variable AC output frequencies. At high frequencies, the arc cone is much tighter and more focused. The result is a significantly improved arc stability, ideal for fillet welds and other fit ups requiring precise penetration. On the other hand, work pieces with

wider gaps to fill benefit from a softer, wider arc cone produced by low frequencies. In general, the ideal frequency range for most aluminium welding applications is 120 to 200 Hz.

1.1.3   Plasma welding

Plasma welding differs from TIG welding in that the arc consists of a plasma, i.e. a gas with positive (ions) and negative (electrons) charge carriers. The plasma arc is constricted by a water-cooled, fine-bore copper nozzle which squeezes the arc and thus improves arc stability, arc shape and heat transfer characteristics. Because the electrode is positioned within the torch body, the plasma arc can be separated from the shielding gas envelope. The plasma gas is normally argon; for shielding, argon or argon/helium mixtures are used.
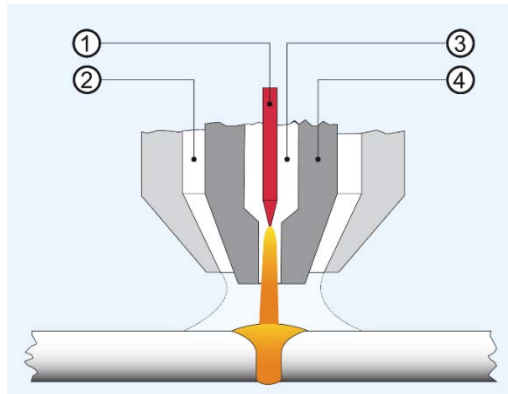
Plasma arc welding process: (1) Tungsten electrode, (2) Shielding gas, (3) Plasma gas, (4) Plasma nozzle

(Source: Fronius)

The plasma torch delivers a high heat concentration to a small area, i.e. plasma welding offers a deep penetration effect and results in low geometrical distortion. Filler metal may be added in the same way as with TIG welding.

The plasma arc is normally operated with a DC power source. The variable polarity technology combines the advantages of negative electrode polarity to minimize heat produced in the electrode with the benefits of arc cleaning provided by periodic bursts of positive electrode energy.

Three operating modes can be realised by varying welding current, nozzle diameter and plasma gas flow rate:

- **Micro-plasma welding**

    Micro-plasma arc welding operates at very low welding currents (0.1 to 15 A). It is used for manual welding of very thin sheets (down to 0.1 mm thickness). The needle-like, stiff arc minimises arc wandering and distortion. Both manual and mechanized utilization is possible.

- **Plasma welding with medium current**

    At medium currents (15 to 200 A), the process characteristics of the plasma arc are comparable to those of the TIG arc, but the arc is stiffer. The advantages are a deep weld penetration and greater tolerance to surface contamination (including coatings). The main disadvantage is the bulkiness of the torch, making manual welding difficult.

- **Keyhole plasma welding**

    A further increase of welding current and plasma gas flow produces a powerful plasma beam which can be used to melt completely through the base material, forming a "keyhole". The forward moving arc melts the leading edge of the keyhole, molten metal flows around the perimeter of the hole and solidifies behind the arc to form the weld bead under surface tension forces.

Compared to TIG welding, keyhole plasma welding offers higher welding speeds and deeper material penetration. The keyhole mode ensures a smooth weld bead profile with no undercut. Proper control of the slope-out of current and plasma gas flow allows to close the keyhole while terminating the weld. Because the welding parameters, the plasma gas flow rate and the filler wire addition must be carefully balanced to maintain keyhole and weld pool stability, this technique is only suitable for automatic, mechanised or robotic welding.

Keyhole plasma welding

(Source: Fronius)

Plasma arc welding is an interesting alternative to laser welding where tough quality demands must be met, especially on sheets and other components with a material thickness of up to 8 - 10 mm. The powerful, constricted arc eliminates or reduces the need for time-consuming weld preparation work such as V- or U-type joint preparation and saves as much as 30 % of the filler metal.

1.1.4   Plasma MIG welding

Plasma MIG welding is a high-performance welding process combining conventional MIG welding with plasma arc welding. However, it is unsuitable for manual welding due to the required large sized welding torches.

The leading plasma arc ensures deep penetration and high efficiency whereas the following MIG arc accounts for the necessary deposition rate to finish the weld. The result is an increased welding speed and an extremely good weld quality, especially the absence of porosity. The high heat input improves gap bridging, but may lead to thermal distortion of the work piece. MIG plasma welding is applied only in special cases, e.g. for aluminium components with large wall thicknesses. It is possible to carry out butt welds of up to 10 mm thickness in one pass.
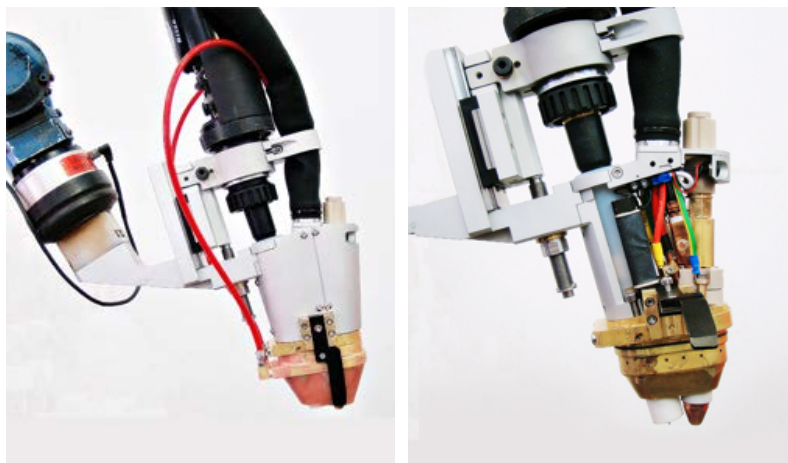
Super-MIG• processing torch

(Source: Plasma Laser Technologies)

1.1.5   Arc stud welding

Aluminium stud welding may be accomplished with conventional capacitor discharge arc stud welding equipment, using either the tip ignition or drawn arc ignition techniques. An aluminium stud welding gun is normally equipped with a special adapter for the control of the shielding gases used during the welding cycle.

The standard diameter of aluminium studs varies ranges between 1.5 and 7 mm. A small cylindrical or cone shaped projection at the end of the aluminium stud initiates the arc. The short arcing time of the capacitor discharge process results only in a shallow penetration; the minimum work piece thickness is 0.8 – 1 mm.

Aluminium studs and stud welding gun for semi-automated applications

(Source: Stanley)

1.1.6   General remarks

In the following, some specific joining standards and guidelines referring to aluminium arc welding are mentioned, however, since the present manual is general in nature and meant for informative purposes, no claim to be complete is made or intended.

Manual and automatic arc welding

Manual welding is used for all welds when mechanisation/automation is not considered to be profitable (e.g. low production volumes, complex weld configurations, repair welding) and the dimensions and thickness of the products are compatible with the selected welding process. If applicable, a hand-held rod may be used to add the filler metal to the weld pool in TIG welding whereas in MIG welding, the consumable electrode is always automatically fed from a reel.

Mechanised welding is ideal for large and heavy products. The welding parameters are controlled mechanically or electronically and may be manually varied during welding to maintain the required welding position.

In automatic welding, all welding parameters are controlled. Manual adjustments may be made between welding operations, but not during welding. Potential applications are long straight welds. The result is a consistent weld quality and an attractive appearance of the weld bead, if the welding parameters are properly defined. Generally, a human operator prepares the materials to be welded.

Robotic welding uses a robot that can be pre-programmed to different welding paths and fabrication geometries. The welding process is completely automated as robots both perform the weld and handle the parts. Robotic welding is commonly used for high production applications.

Successful application of mechanised and/or fully automated systems offers increased productivity, consistent weld quality and reduced welding costs. Limitations include higher capital investment than for manual welding equipment, the need for more accurate part positioning, and more sophisticated arc movement and control devices.

Mechanised longitudinal seam welding (left) and robotic welding of an aluminium tank (right)

(Source: EWM Hightec Welding GmbH / Carl Cloos Schweisstechnik GmbH)

Joint design for fusion welding

The design of aluminium joints for arc welding is quite consistent with that for steel joints. The choice of the joint configuration depends on the principle stresses acting on the joint, but also on various other factors (material thickness, geometrical tolerances, accessible torch positions, clamping possibilities, etc.). Shear stress should be largely avoided because most joints are very sensitive to this kind of loading. Specific design guidelines for railway vehicles are given in: «Gestaltung und Festigkeitsbewertung von Schweissverbindungen an Aluminiumlegierungen im Schienenfahrzeugbau» (DVS 1608) (Sept. 2011). Most important is also the size of the welding torch and the arcing characteristics which are often overlooked in the initial design stage.

However, compared to steel, the higher fluidity of aluminium must be kept in mind when selecting the proper type of joint preparation and dimensions. For light gauge materials, little groove spacing must be ensured. A specially designed V groove is advantageous when a smooth, penetrating bead is desired and welding can be done from one side only. It should be applied on all materials with a thickness higher than 3 – 4 mm. For fully penetrating welds, comprehensive recommendations for joint preparation are given in EN ISO 9692-3. Some indicative examples are given below, however, alternative solutions are also possible.

The aluminium extrusion technology offers some interesting possibilities to simplify the welding process. Innovative cross section design may include edge preparation, material compensation, in-built fastening, integral root backing and minimization of the required number of welds.

Edge preparation for arc welding

Proper preparation of the weld joint helps to produce a sound weld and meet the quality requirements. Different cutting methods can be used, including shearing, sawing, fluid jet cutting, laser or plasma cutting. Ground or smeared cutting surfaces should be avoided since they may cause lack of fusion. For high quality welds, it is recommended to machine the edges to be welded to remove rough surfaces with thicker oxide layers and/or micro cracks. Edges should be carefully de-burred to avoid sharp notches, especially at the root of the weld. The use of milling tools is preferred since surface residues of a grinding disc can cause weld porosity.

Process	Welding position	Weld bead	Thickness	Preparation	Remarks
TIG	All positions	One side only	0.8 < t <1.5		A slight peak formed by the edges limits deformation
TIG	Horizontal	One side only	0.8 < t < 5		Chamfered card, stainless steel support, clamped weld
TIG	All positions	One side only back-weld possible	1.5 < t < 5		Tack-welded free edges
TIG	All positions	One side only	4 < t < 6	80° / 2 mm / 1 mm	Tack-welded free edges. Angle same principle but with offset bevel
MIG	All positions	One side only with back-weld	2.5 < t < 6	1 mm	Back-weld necessary after gouging to base of first pass
MIG	All positions	One side only	2.5 < t < 6		Stainless steel support
MIG	All positions	One side only	2.5 < t < 6	e / e	
MIG	Horizontal and overhead*	One side only with back-weld	6 < t < 25	80° / 2 mm / 1 mm	Back-weld necessary after gouging to base of first pass. Clearance: 1.5 mm max.
MIG	Horizontal and vertical*	One side only	4 < t < 25	80° / 1 mm	Ribbed stainless steel support

* X-shaped bevels are preferred for components 6 mm < t < 25 mm to restrict deformation due to welding.

Edge preparation for MIG and TIG welding (examples)

Prevention of deformation

Ideally, there should be as little welding as possible. Excessive welding can be avoided at the design stage using bigger, more integrated aluminium components.

Weld distortions are caused by localized expansion and contraction of the structure as it is heated and cooled during welding. The determining factors include the size and shape of the welds and their location in the structure, the heat input rate, the size and wall thickness of the components being welded, the assembly sequence, and others. Minimum geometrical distortion of the assembled structure is primarily ensured by the order in which the welds are performed ("welding plan"). Low heat input and symmetrical welding must be envisaged as well as the use of fixtures that provide even cooling. An appropriate method to prevent distortion is the use of specialized computer programs which predict residual stresses and geometrical distortion after welding, allowing optimization of weld sequence and/or clamping conditions. Dimensional tolerances can be minimized by clamping machined components on datum points; then connecting them with welds allowing for sufficient slip in the critical directions. Robotic welds are more reproducible then manual welds and allow systematic reduction of tolerances by adjustments of the datum points in the fixtures. Attention to good joint fit-up and joint accessibility are other important considerations.

Surface preparation

A most critical step is a proper cleaning of the weld surface. The surface must be dry and free from oil, grease, paint, dirt, oxides, and other foreign material. Cleaning solutions, wire brushes, and abrasive blasting are some of the methods used to remove these contaminants. Outdoor welding is not advisable. If it cannot be avoided, the welding environment must be screened off.

Choice of filler wire or rod

Filler metal is usually added also in TIG welding although most non-heat treatable aluminium alloys could be TIG welded without adding a filler. Proper selection of the filler alloy is a main consideration. Normally, Al-Si and Al-Mg filler alloy wires and rods are used, namely EN AW 4043A, 4045, 4047A, 5183, 5356 and 5556A (see also ISO 18273 which specifies requirements for classification of solid wires and rods for fusion welding of aluminium and aluminium alloys).

Each combination has three possible choices - indicated where the lines intersect - depending on the selected criterion:
Optimum mechanical properties: top line – Optimum resistance to corrosion: middle line – Optimum weld-ability: bottom line
The filler metal indicated is: 4 : series 4xxx → 4043A, 4045, 4047A – 5 : series 5xxx → 5356, 5183, 5556A

Alloy A	Wrought 5000 Series Mg < 3%	Wrought 5000 Series Mg > 3%	Wrought 6000 Series	Wrought 7000 Series without copper	Cast Si > 7% (c)
Wrought 5000 Series Mg < 3%	5 5 (a) 4 - 5 (b)				
Wrought 5000 Series Mg > 3% (a)	5 5 5	5 5 5			
Wrought 6000 Series	5 - 4 5 4	5 - 4 5 4	5 - 4 5 4		
Wrought 7000 Series without copper	5 - 4 5 4	5 - 4 5 4	5 - 4 5 4	5 - 4	
Cast Si > 7% (c)	4 (e) 4 4	5 - 4 (e) 5 4	4 4 4	4	4 (d) 4 4

(a) 5000 series alloys with more than 3.5% Mg are sensitive to intergranular corrosion when exposed to temperatures over 65ºC and when used in certain aggressive environments (see section 2.2.6 in Chapter XI).

(b) 5000 series alloys with less than 3% Mg and 3000 series alloys that contain magnesium may be sensitive to hot cracking.

(c) The mechanical performance of the weld depends on the internal soundness of the castings. Gassed materials and injection mouldings are considered to be non-weldable.

(d) The percentage of silicon in the filler wire must be as near as possible to that in the casting.

(e) The welding of aluminium-silicon castings (40000 series) to 5000 series alloys should be avoided where possible as Mg2Si inter-metallics form in the weldment and weaken the joint.

Choice of filler metals as a function of the alloy combination

When considering welding of specific aluminium alloys or aluminium alloy combinations, selection criteria for the filler alloy typically include ease of welding, strength and ductility of the welded joint, corrosion resistance, visual appearance, etc. Consultation of a filler metal chart is strongly recommended.

The weld consumables should be stored in sealed packages and once a package is open, it must be kept in a clean and dry atmosphere with an ambient temperature. Humidity on the surface of the wire or rod causes porosity in the weld. When handling, gloves should be used to protect the filler metals from any moisture or oils.

Quality control

Quality control enables manufacturers to evaluate the quality of the fabricated product and more specifically to grade the quality of a welded joint against an acceptable level of defined defects.

Welders must be certified and qualified in accordance with EN ISO 17024. Welding procedure specification must be in accordance with EN ISO 15609-1, EN ISO 15612, EN ISO 15613 and EN ISO15614-2. Test specimens must be submitted for tensile or bending tests. It may also be prudent to perform some destructive tests on reference specimens.

The level of acceptable defects is determined by the type and direction of the loads, the stress levels, the potential hazards, the possibility of routine operational inspection, etc. The relevant approval procedures may be defined by application-specific standards, agreed between client and supplier or self-regulated by the fabricator.

Approval criteria for weld defects and quality levels are described in EN ISO 10042, guidance for the choice of the required quality level is given in EN 1090-3. An international nomenclature of weld defects is given in EN ISO 6520-1.

N°	Type of Defect	Likely Cause	Photos of Imperfections
101	Cracks	Base alloy unsuitable Poor choice of filler metal Incorrect welding sequence Excessive clamping Sudden cooling	
104	Crater cracks	Pass finished with sudden arc cutoff	
2012	Irregular wormholes	Work inadequately degreased Work and/or filler wire dirty or wet Insufficient protection by inert gas (low gas flow or leak in the system) Pass begun on cold component High arc voltage Weld cooled too quickly	
2014	Aligned wormholes	Incomplete penetration (double pass) Temperature gradient between backing and work too abrupt Excessive gap between edges of the joint	
300	Solid inclusions	Dirty metal (oxides, brush hairs)	
303	Oxide inclusions	Poor gas shielding Metal stored in poor conditions Castings	

3041	Tungsten inclusions (TIG)	Electrode diameter too small Poor handling by welder Excessive current density Poor quality of tungsten electrode	
402	Incomplete penetration	Inadequate cleaning (presence of oxide) Incorrect bevel preparation on thick work (too tight, excessive shoulder) Gap between workpieces too small (or incon-sistent) Low current, especially at the start of the seam Welding speed too fast High arc voltage	Defect 300 Defect 402
4011	Lack of fusion on edges	High arc voltage Low current, especially at the start of the seam Work cold (difference in thickness between materials to be welded)	Defect 402
502	Excessive thickness	Poor power control (poor U/I match) Welding speed too slow Poor edge preparation on thick work Insufficient starting current	Defect 502
507	Misalignment	Work positioned incorrectly Incorrect welding sequence	
508	Angle defect	Excessive welding power Incorrect welding sequence	
509	Collapse	Wire speed too fast Torch speed too slow Poor torch guidance	
602	Splatter (or beads)	Incorrect arc control Problem in electrical contact to ground	Defect 507

Common weld defect and their causes

1.2   Laser and electron beam welding

Electron and laser beams provide a localized high power density, allowing for narrow, deep penetration welds and high welding speeds with minimal power input. The localized heat input leads to small heat-affected zones, reduced geometrical distortions and low residual stresses. For structural welding, mechanised or robotic welding systems are exclusively used.

1.2.1 Electron beam welding

Electron beam welding is usually carried out in a vacuum chamber, but there are also non-vacuum welding systems. No filler metal is used as the high thermal gradient from the weld into the base metal creates only limited metallurgical modifications. Preferred joint geometries are lap and simple butt joints.

The central issue of electron beam welding is the concurrent emission of X rays. In vacuum electron beam welding, the vacuum chamber provides the necessary protection whereas the working area of a non-vacuum electron beam welding machine must be shielded by lead walls.

Electron beam welding under vacuum

Welding depths up to 300 mm with depth-width-ratios of 50:1 can be achieved in a single pass at high speeds (>>10 m/min). Welding in vacuum ensures a clean and reproducible environment and protects the molten metal. The beam is moved over the work piece either by electromagnetic deflection or mechanical motion and the working distance can be varied over a wide range. However, the need for an evacuated chamber and long handling times drastically hinder application for large parts and reduce productivity.

Non-vacuum electron beam welding

In non-vacuum electron beam welding, the electron beam emerges from the gun column via a series of differentially pumped vacuum stages which are separated by small diameter orifices. The working distance is fixed (5 – 25 mm), i.e. differences in working distance must be equalized by moving the electron beam generator. A shielding gas (helium or argon) is necessary to protect the weld pool.

Non-vacuum electron beam welding is typically applied for thin metal parts (up to 5 - 10 mm thickness). Deep penetration welds with depth-width-ratios of 5:1 can be realized at atmospheric pressure with weld characteristics like those produced by vacuum welding. The diverging electron beam permits good gap bridging; gaps between 0.1 up to 1 mm can be tolerated depending on the joint design, material thickness and welding speed.

1.2.2 Laser beam welding

Laser beam welding offers significant advantages in industrial application since the laser beam transmits through air, the requirements for occupational safety are lower (although proper eye protection is a necessity) and the process can be easily automated using standard robots. The weld characteristics are similar as in electron beam welding, but penetration depth as well as welding speed are lower. A shielding gas protects the molten metal pool from oxidation and environmental contamination.

With aluminium, laser beam welding is typically applied to the thickness range 0.5 – 4 mm, but also joints requiring at least 10 mm penetration can be realized at speeds ranging from 2 to > 10 m/min. Solid state lasers are generally used except for welding depths > 6 – 8 mm where CO_2 lasers are more efficient.

Laser welding cell

(Source: Trumpf)

Due to the small spot size, laser welding is particularly suited for overlap and fillet joints. Compared to resistance spot welding, laser welding allows significantly shorter flanges. For butt welds, the acceptable gap tolerance must be as small as possible.

Heat conduction welding

Heat conduction welding is the typical operation mode at lower power densities. The absorption of the laser energy causes melting of the material surface and the solidifying melt joins the mating parts. Weld penetration

depth is below 1 to 2 mm. The laser produces a smooth, rounded bead that does not require extra grinding or finishing. The heat-affected zone is relatively wide and the transition from the fusion zone to the base metal is smooth and gradual.

Deep penetration welding

Deep penetration welding requires a higher power density. Once the metal temperature rises above its boiling point, metal vapour is generated and the vapour pressure opens a channel around the laser beam. The result is a deep, vapour-filled capillary ("keyhole") approx. 1.5 times the diameter of the focal spot of the laser beam surrounded by molten metal. As the laser beam advances along the weld joint, the keyhole moves with it through the work piece. The molten metal flows around the keyhole and solidifies in its trail.

Deep penetration welding is distinguished by great efficiency and high welding speeds. The weld depth may be up to ten times greater than the weld width. The heat-affected zone is small and there is minimum distortion.

Twin laser welding

The weld quality and process stability can be increased by the use of two laser beams, focussed at the same spot. The result is a higher positioning and gap tolerance, particularly useful for butt joint welding.

Remote laser welding

Remote laser welding uses scan mirrors to position the beam precisely at the desired location and for quick decoupling in between welds. This allows the realisation of highly flexible production lines and productivity increases by a factor of 3x - 5x over conventional laser welding. The high beam quality available with solid state (diode, disk or fibre) laser systems, combined with a fibre light transport system and a beam-expanding telescope, provides for the required focused spot diameter even with a focal length of > 1 m. The programmable focusing optics can be guided over a work piece with an industrial robot, permitting true three-dimensional part processing.
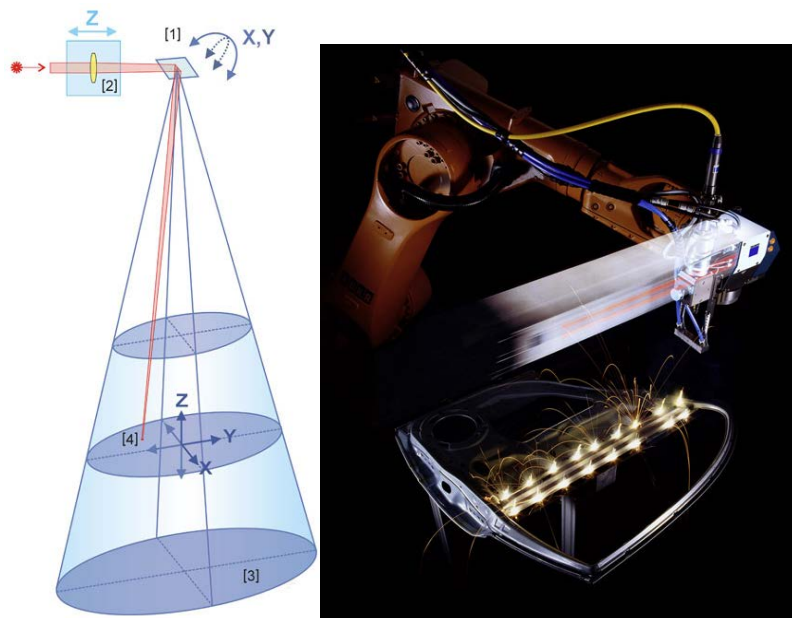
Laser scanner welding

(Source: Trumpf)

Filler metal addition

Laser beam welding is preferably carried out without the addition of a filler metal. However, in many cases, a filler metal must be added either for metallurgical reasons or to accommodate larger gaps. In practice, sophisticated

coordination between beam and wire feeding positioning mechanisms and the optical seam tracking device is necessary.

The wire feeding mechanism is generally attached to a robot arm together with the laser head. In remote laser welding, however, this approach will not work because the distance between the laser head and the weld location is too large. A solution was found with the development of multi-layer alloy sheets which include a filler metal layer and enable to bridge up to 0.4 mm wide gaps at welding speeds over 20 m/s. Multi-layered alloy sheets also allow welding through with only 5 mm distance to the edge.

1.2.3 Laser MIG welding

The combination of a standard arc welding process with laser welding benefits from the advantages of both techniques. The laser beam runs ahead of the MIG arc, but both focus on the same point of the metal surface. Laser MIG hybrid welding is ideal for continuous automatic welds of up to 10 mm thickness in one pass.

Laser – MIG welding head

(Source: Fronius)

The process is controlled in such a way that the MIG arc provides the appropriate amount of molten filler material to bridge the gap and to close the joint, while the laser delivers the high-power densities needed to ensure the desired penetration depth and the high welding speed. The hybrid technique is faster than MIG welding alone, the fit-up requirements are less stringent and the joined components are subject to less distortion.

1.3 Resistance spot welding

Resistance spot welding utilizes the heat produced by the resistance to the flow of electric current. The work pieces are overlapped and held together under pressure exerted by two shaped copper electrodes. Local melting occurs preferentially at the interface of the work pieces and the faying surfaces are connected by the solidifying nugget. Resistance spot welding is characterized by very short process times and readily adapted to automation.

Spot welds should always be designed to carry shear loads. When tension or combined loadings may be expected, special tests must be conducted to determine the actual joint strength under service loading. In such applications, resistance spot welding is often combined with adhesive bonding (see section 4.3).

Resistance spot welding of aluminium

The high thermal and electric conductivity of aluminium alloys asks for a significantly higher welding current than for spot welding steels. Suitable chemical surface treatments, often applied by the material supplier, provide a consistent, medium to high surface resistance. Nevertheless, the surface of the copper electrode tip deteriorates more rapidly as the result of the high pressure, high temperature and alloying processes. But the electrode life time can be significantly enhanced by regular electrode dressing, typically completed during the part transfer

operation. Compared to self-piercing riveting (section 3.2.2), resistance spot welding is more flexible in terms of thicknesses and stack-ups that can be joined with one gun, reducing investment and piece cost per assembly.

Welding equipment suitable for aluminium resistance spot welding can readily weld steel to steel just by loading different control parameters, offering very flexible joining of mixed-material aluminium-steel designs.
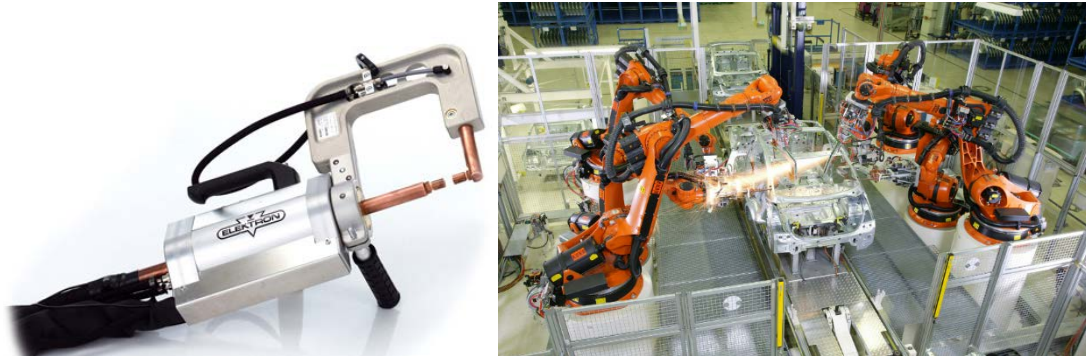
Manual resistance spot welder (left) and robot spot welding system (right)

(Source: Elektron/ Kuka Systems)

*Resistance spot welding with a process tape*

Rapid electrode deterioration can be avoided by resistance spot welding with an intermediate layer ("Fronius DeltaSpot"). The process tape runs between the electrode and the work pieces, in the same rhythm as the spot welding operation. After every spot, the "used" length of the process tape is moved out of the contact zone, i.e. the starting conditions for the next spot are always the same.

2. Friction stir welding

Friction stir welding is a solid-state joining process, developed and patented by TWI, which creates high-quality, high-strength joints with low distortion. A rotating cylindrical tool with a profiled pin is plunged into the joint area between the two work pieces. As the tool plunges into the material, the heat generated by friction and plastic deformation causes the formation of a strong metallic bond at temperatures below the melting point. of the work piece materials.

Linear friction stir welding

The parts to be joined are securely clamped to prevent the joint faces from being forced apart. The heat generated by the constantly rotating, wear resistant tool "softens" the adjacent material, allowing the tool to traverse along the joint line. As the pin moves forward, the special profile on its leading face forces the plasticized material to the trailing edge of the tool pin and the two work pieces are essentially forged together by the clamping forces, assisted by the mechanical pressure applied by the tool shoulder and pin profile. The surface of the finished weld is smooth and virtually flush with the part surface.
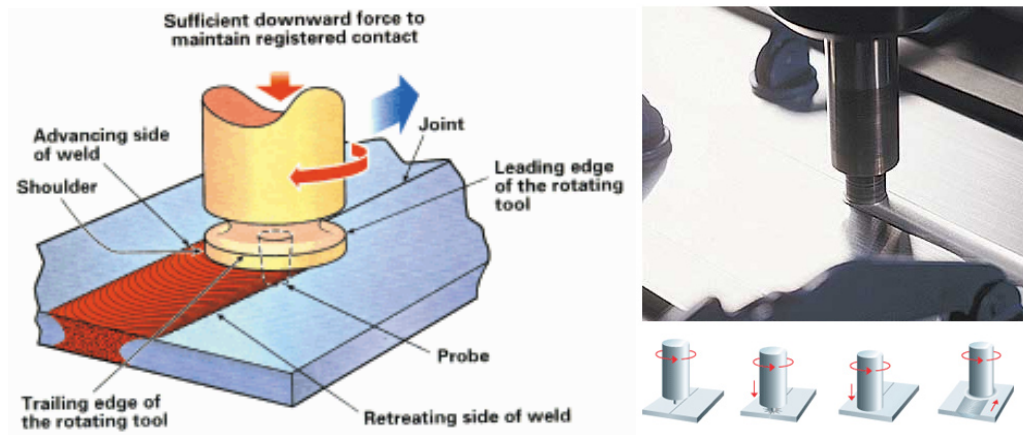
Linear friction stir welding process

(Source: TWI / Sapa)

The process can be used for butt, overlap and corner joints. Specific tool designs are necessary for each joint geometry. Material thicknesses ranging from 0.5 to 65 mm can be joined from one side at full penetration, without porosity or internal voids.

Friction stir welding is a highly suitable technology to join aluminium components without using filler wire or shielding gas. The relevant process parameters are purely mechanical (force, friction, and rotation). The most important control feature is the down force which guarantees high quality even where dimensional tolerances of the work pieces are relatively large. Other process parameters to be controlled are traverse speed, rotation speed and tilting angle of the tool. Typical joining speeds with production machines are about 2000 mm/min (e.g. for extruded aluminium profiles with a wall thicknesses of about 2 mm). With increasing material thickness, speed decreases correspondingly.

The quality of friction stir welded joints is generally superior to that of conventional fusion-welded joints regarding strength and ductility. Different process variants offering either improvements in quality, productivity or optimised performance are available for specific tasks. However, it should be noted that, in practice, the high forces practically limit the method to welding in a plane. Three-dimensional assemblies would require unpractically massive fixtures.

Friction stir spot welding

Overlap joints of aluminium parts with material thicknesses ranging from 1 - 3 mm can be produced when the rotating tool is kept to one spot. Friction stir spot welding produces a joint strength comparable to that produced by resistance spot welding (better than clinched spots, but less than self-piercing rivets). A disadvantage is the characteristic keyhole in the spot centre, which significantly decreases the mechanical properties.

Friction stud welding

In its simplest form, friction stud welding involves rotating a stud in the form of a solid rod and forcing it onto the work piece surface. The resulting frictional heat causes material plasticisation in the contact region. Rotation of the stud is then stopped and the maintained axial force consolidates the joint. Process time is very short and the weld quality is consistently high.

3. Mechanical joining

The advantages of mechanical joining methods include applicability for materials difficult to weld and for dissimilar material combinations, minimum geometrical distortion, little or no damage to pre-coated materials and no fume or heat generation, low noise emission, low energy consumption, etc.

Sealants are often used to prevent crevice corrosion of the sandwiched metals. Whilst mechanical joints alone would produce the necessary strength, the use of a suitable adhesives (which acts simultaneously as a sealant) may further improve performance.

## 3.1 Mechanical joining without additional fastener

3.1.1 Hemming

Hemming is normally used to join two sheet metal parts, e.g. in the fabrication of closure panels. In conventional die hemming, the flange is folded over the entire length with a hemming tool. In roll hemming, the hemming roller is guided by an industrial robot to form the flange.

3.1.2 Clinching

Clinching is a high-speed method to join two or more thin-walled materials by local plastic deformation. A punch pushes the layered metals into a die, forming an interlocking friction joint with good static and dynamic strength.

The clinching process is applicable from a single sheet thickness of 0.1 mm up to a total layer thickness of 12 mm. It requires open flanges with good access to both sides. The preferred joining directions are: "Thick into thin material" and "High into low strength". Since clinching is a cold forming process, the formability of the involved materials must be sufficiently high (normally $A_{80} \geq 12$ %). A dry, grease-free surface will give a stronger joint than an oily or wet surface. On the other hand, minimum lubrication avoids adhesion of aluminium to the tool and significantly improves the tool life. Thus, a suitable compromise must be found.
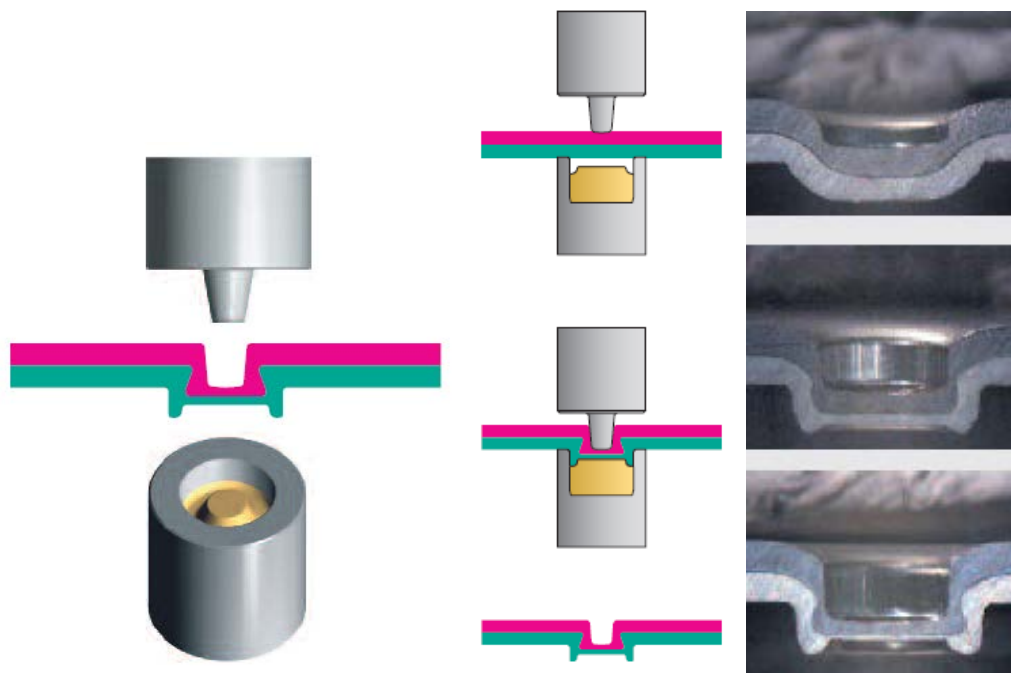
TOX$^{\circ}$ round clinch joint, a one-step process with a solid die

(Source: TOX Pressotechnik)

Clinching is primarily used in non-crash-relevant areas. The properties of a clinched joint depend on the applied tools and the specific joining parameters as well as the material properties. Prior laboratory tests of the specific joint arrangement are recommended to determine the relevant design parameter.

Clinching systems come in all sizes and types (with and without local incision); the equipment ranges from handheld units to multi-head systems with double-acting punch and dies, and self-centring heads. The quality of the clinched joint is tested by measuring the residual base thickness and the joint diameter on the die side. Integrated force-displacement or force-time monitoring can be implemented to guarantee comprehensive quality assurance.

3.1.3 Mechanical interlocking

The snap-lock design uses serrated components making assembly easy and quick. Due to its elasticity, aluminium is highly suited to realise snap-fit joints, allowing far quicker assembly than, for example, screw or welded joints. Snap-fit joints are a most interesting to join extruded aluminium profiles as well as extruded aluminium and plastic sections. Stresses are distributed over the entire length of the profile and not merely concentrated on the mechanical fixtures. Relevant application areas can be found primarily in the floor structure, the sidings and in the interior.

Latitudinal joining using with a snap-fit (left and centre) or screw ports (right)

(Source: Sapa)

3.2 Mechanical joining with an additional fastener

Mechanical assembly methods using an additional fastener are classified according to their functionality and the accessibility of the joint. A further differentiation can be made between methods requiring a pre-fabricated hole and self-piercing fastening elements.

3.2.1 Screws and bolts

Screw joints are detachable joints which require either a separately manufactured mating thread or an extra, internally threaded component (nut). A distinction can be made between connections formed using a clearance hole (bolts) and internally threaded holes (screws). Since aluminium alloys show relatively low compressive strength, the contact surfaces must be generally protected by washers under the screw and the nut.

Threaded fasteners are widely used and manufactured in a wide variety of shapes and sizes. Application methods range from manual use to fully automated (robotic) systems. For aluminium structures, screws and bolts are usually made of steel, but also other materials (including high strength aluminium alloys) can be used. When regular disassembly is required, steel fasteners should be applied. Except for aluminium and stainless steel fastening elements, they must be coated to prevent galvanic corrosion.

Bolted connections

Connections may be produced by simply bolting through the aluminium parts. If bolting through a closed section, it may be necessary to provide an internal support to prevent the section from collapse under high installation loads.

A special benefit of the aluminium extrusion technology is the possibility to integrate continuous tracks for nuts or bolt heads into the cross section of the profile enabling step-less fastening without any need to machine the profile. Using special nuts/bolts, fastening can even take place without having to slide in the nut/bolt from the end of the track.
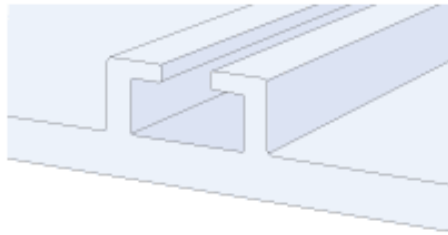
Continuous tracks for step-less bolting in extruded profiles and special nuts/bolts

(Source: Sapa)

Female threads in aluminium components

The load-bearing resistance of a joint formed between a bolt and a machined thread depends not only on the strength of the material, but also on the form of the thread and the area of the mating surfaces. When the threads are cut or cleanly grooved into wrought aluminium components, the screws can be undone and tightened up repeatedly without damaging the thread. In low-strength aluminium alloys and aluminium castings, steel thread inserts may be used to increase the pull-out force and facilitate assembly and disassembly.

Threaded studs and nuts

Bolted connections can also be made with threaded studs and nuts which are previously fixed to an aluminium component. Such solutions are applied when tapped threads are not possible due to small wall thicknesses or when the material is too soft to support tapped threads. The applied threaded elements take on the role of either the nut or the bolt and enable the attachment of further components in a second step. The selection of the insert type depends upon the required strength and whether access is possible from one or both sides.

Aluminium threads may be applied for lightly loaded connections whereas steel threaded studs and nuts are preferred for applications where higher strength or frequent disassembly is necessary. Aluminium studs and nuts can be welded directly to the aluminium parts, e.g. by electric arc welding. However, most threaded studs and nuts are mechanically attached. They may be installed at any stage in the assembly sequence (including in-service repair); installation may be also incorporated into a part forming operation.
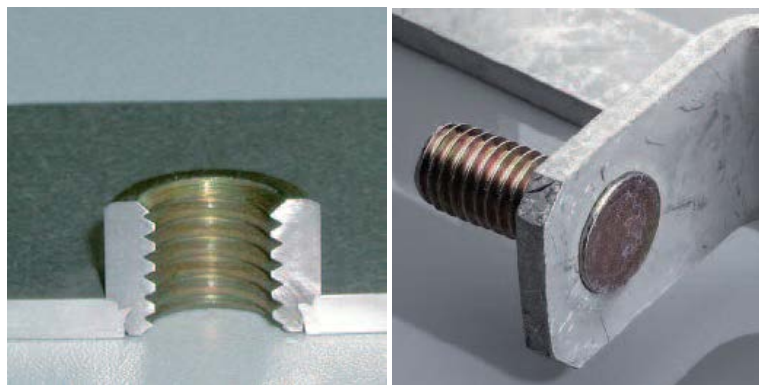

Installed press-in nuts and studs (Clifa® system)

(Source: Kerb-Konus)

Press-in elements using pre-punched holes are used in thin-walled work pieces with thicknesses above 0.8 mm up to 6 - 8 mm. When attached by riveting, functional elements ensure torque-resistant connections capable of withstanding loads from both sides. Self-piercing elements are typically applied for thin sheets (< 2.5 mm), but special designs are applicable for higher thicknesses.

Blind rivet nuts and bolts

Blind rivet nuts and bolts are inserted from one side into a pre-punched hole and rapidly set with a processing tool. They are mounted without counter pressure and can therefore also be set into hollow sections.
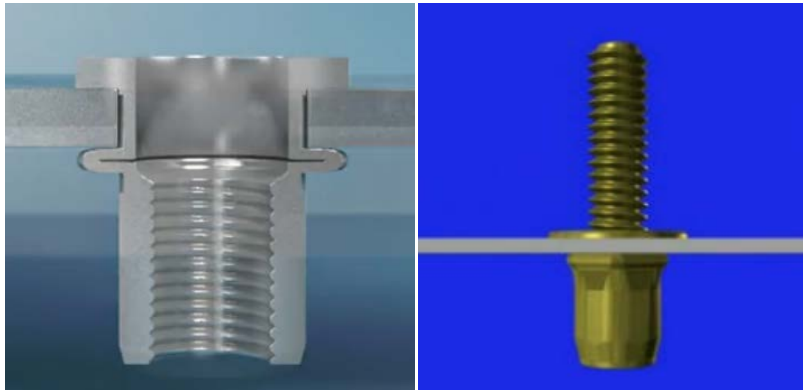
Blind riveting nut and bolt, installed by upsetting

(Source: Böllhoff)

Most blind rivet inserts are installed by upsetting. During installation, the insert collapses into a buckled fold on the backside of the application material, trapping the material between its flange and the backside fold. The result is a high resistance to pull-out loads. Another type of blind rivet design relies on flared legs expanding outwards with a threaded inner ring to attach the other work piece. It is specifically used where a distributed load is required. A third option is the expanding insert; a single piece which breaks into two pieces during installation. The lower, threaded section of the insert is drawn up inside the upper sleeve section, causing the sleeve to expand over its entire circumference, thus swaging the insert into the hole. It shows a reduced rear-sheet protrusion, but offers less resistance to push-out forces.

Self-tapping screws

Self-tapping screws form their own threads when screwed into core holes prepared either as a blind hole in full material or as a pre-punched hole in sheet metal. They are highly suited for joining thicker aluminium components, increasing productivity and reducing joining cost. For thin sheet applications, prior formation of a rim should be considered. In extruded aluminium profiles or castings, screw ports for transverse and longitudinal connections can be directly integrated into the component.


Self-tapping screw

(Source: Böllhoff / EJOT)

Hole and thread forming screws

Hole and thread forming screws eliminate the drilling operation and enable high strength joints due to the increased thread engagement in the formed draught. Joining of aluminium components with up to 5 mm thickness is generally possible. For specific material combinations, a pilot hole may be advantageous.

The usual tolerance problems as overlapping of draught and insertion hole do not apply. One-sided accessibility provides also for an assembly into hollow profiles without any counter support. Hole and thread forming screws are highly suited for automated assembly. Stainless steel screws are most often used.
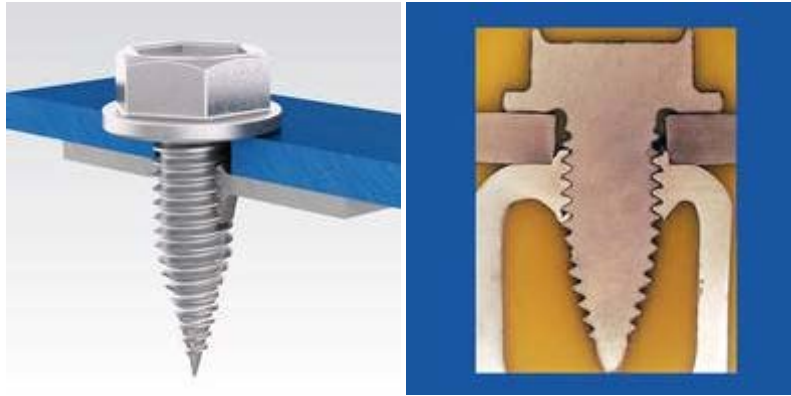
Hole and thread forming screws for thin sheet metal

(Source: Betzer)

There are essentially two different methods:
- Cold hole and thread forming screws exhibit a sophisticated screw design. The special geometry of the screw point produces a high contact pressure per unit area which then leads to the necessary plastic deformation of the material.

- In the flow forming (drilling) process, a tapered, but unthreaded punch rotating at high speed is forced down to pierce through the metal. The sheet metal heats up and a collared hole is formed by plastic deformation. A thread can then be tapped into the cylindrical hole.

3.2.2 Rivets

Rivets are permanent mechanical fasteners which clamp two or more material layers together. Riveting is a safe and easy-to-apply technique, also applicable to mixed material joints. Pneumatic, hydraulic, manual or electromagnetic processes are all highly effective in driving the rivets. Assembly systems range from hand tools and simple work stations to fully automated systems.

Solid rivets

The application of solid rivets requires pre-punched or pre-drilled holes as well as two-sided access. Before being installed, a solid rivet consists of a cylindrical shaft (or shank) with a head on one end. Once the rivet has been inserted, the closing head is formed from the rivet shank by plastic deformation. Because there is effectively a head on each end of an installed rivet, it can support tension loads; however, it is much more capable of supporting shear loads. With all-aluminium constructions, cold-formed aluminium rivets are used almost exclusively.

Blind rivets

Blind rivets are inserted and closed from one side. A blind rivet consists of two components, a smooth, cylindrical rivet body and a solid rod mandrel with a head which runs through the hollow rivet shaft. For installation, the rivet is placed into an installation tool and inserted into the pre-punched hole. The tool pulls the mandrel into the rivet body and the material layers, the rivet walls are expanded and firmly compressed in the hole while a tightly clinched load bearing area is formed on the reverse side. The upset head on the rivet body securely clamps the material layers together. Finally, the mandrel reaches its predetermined break-load, the spent portion of the

mandrel breaks away and is removed. The remaining portion of the mandrel is captured inside the sleeve and plugs the opening in the rivet shell. The entire installation cycle takes about one second.
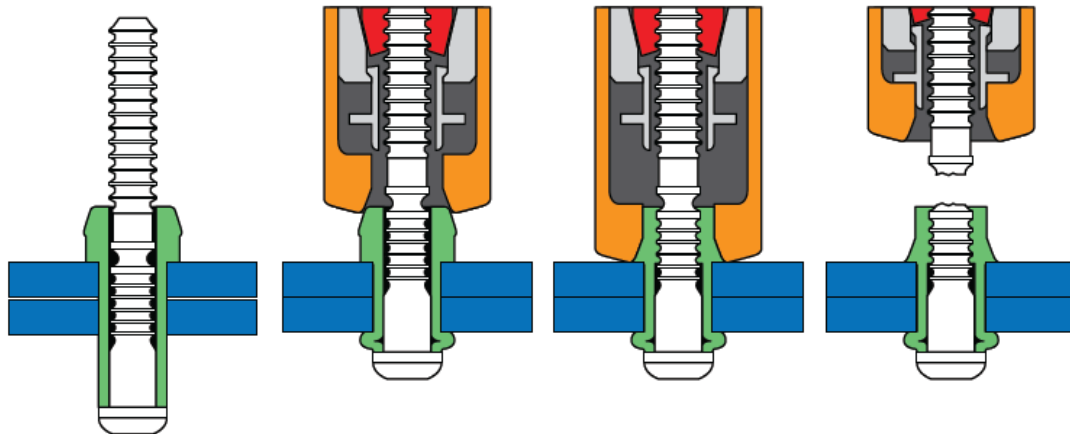

Installation of a high tensile strength blind fastener (BOM®)

(Source: AFS Huck)

Blind rivets are available in different designs both for non-structural and structural applications. Most important is the controlled expansion of the break stem rivet body. This is achieved through an appropriate mandrel design and selection of the rivet material. In aluminium structures, aluminium rivets are normally used. Steel mandrels can be chosen for strength reasons; stainless steel is the preferred option, but there are also steel mandrels with protective coatings.

Lockbolts

Lockbolts require pre-existing holes and two-sided access. They allow the realisation of high strength joints with a high, controlled clamp which will not work loose even during extreme vibration. Lockbolts consist of a pin which is inserted in the hole and a collar which is placed on the pin from the opposite end. The tool is placed over the pintail and when activated, the pin head pulls against the material, the tool anvil pushes the collar against the joint and the initial clamp is generated. The tool then swages the collar into the pin; the pintail breaks and the installation is complete.
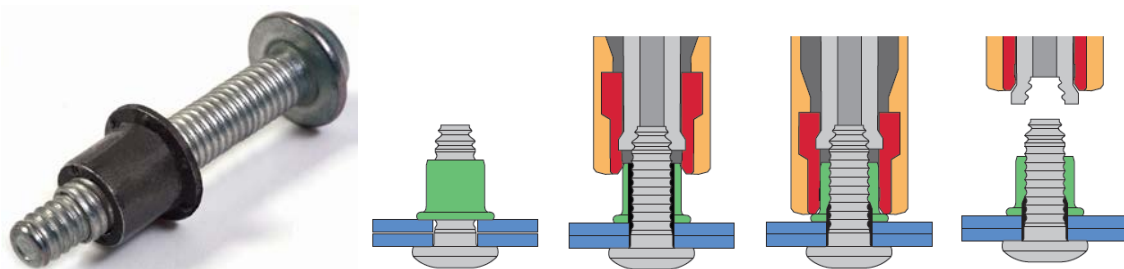

BobTail® lock bolt (left) and installation sequence (right)

(Source: AFS Huck)

Self-piercing semi-tubular rivets

Self-piercing riveting combines the hole-cutting and riveting process. Two-sided access to the work piece is necessary. Self-piercing rivets eliminate the need for alignment and minimize distortion.

The joints need to be of a lap-type configuration. In tensile and peel loading, self-piercing rivet joints have virtually the same static strength as spot welded joints, but show higher strength and stability under dynamic load. In terms of part size or configuration, the only condition is that the rivet actuation cylinder and C-frame can access the joint. Assembly equipment can be stationary, robotic or integrated into an assembly cell.
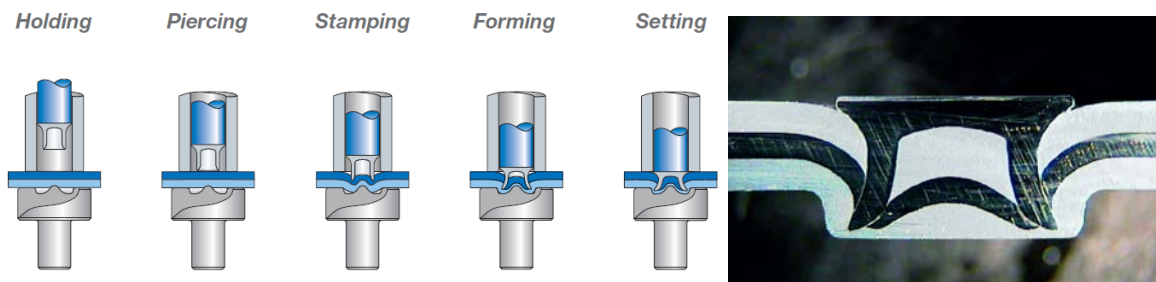
Process sequence for self-piercing riveting with a semi-tubular rivet (left) and three layer Al/steel/Al joint (right)

(Source: Böllhoff)

Semi-tubular rivets pierce the top sheet whereas the lower material layer is not penetrated. A shaped die on the underside reacts to the setting force and causes the rivet tail to flare within the bottom sheet. This produces a mechanical interlock and creates a button in the bottom sheet. For best results, the rivet is applied from the direction of the thin into the thick sheet, or from the low strength into the high strength material. If this is not possible, it is recommended that the bottom layer thickness is not less than one-third the joint stack thickness.

Semi-tubular rivets can fasten stacks of two or more aluminium layers up to 12 mm total thickness. The joint is leak proof and has a very high degree of integrity. Although aluminium self-piercing rivets are available, steel elements covered with a protective layer to prevent galvanic corrosion are generally used.

Self-piercing solid rivets

Self-piercing solid rivets pierce through the whole material stack and the punched-out parts must be removed. Two process variants are used. For rivets without countersunk heads, the rivet is locked by the surrounding material under the compressive action of the shoulders both on the punch and the die. Rivets with a countersunk head show one or more grooves in the rivet shaft and a ring-shaped contour on the die plate presses into the bottom material layer to create the undercut necessary for the connection strength while the punch side remains flat. Nevertheless, the resulting joint strength is inferior to that of semi-tubular riveted joints. Two or more material layers can be joined up to a combined sheet thickness of approximately 9 mm. Aluminium solid punch rivets can be even reworked mechanically.
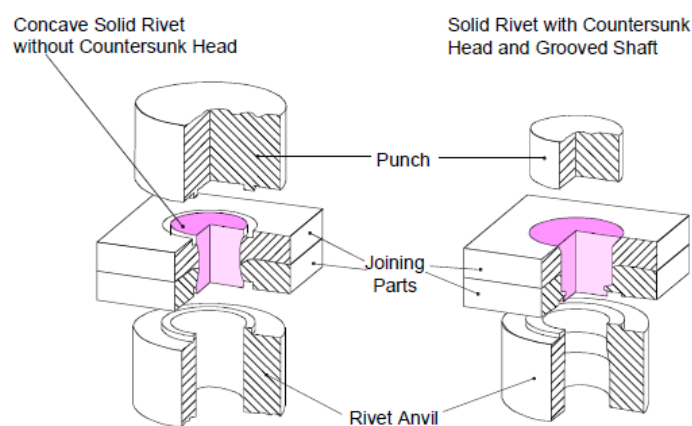

Different form-locking methods when self-piercing riveting with solid rivets

Clinch riveting

The clinch riveting technology complements the clinching process with an additional retaining member. A simple cylindrical rivet is pressed-in and formed during the clinching process. Just like with the clinch joint, the materials to be joined are not cut, but only deformed inside a die cavity. The result is a joint highly suited for shear loading even when used with thin materials.

Tack high-speed joining

Tack joining is a simple and fast joining process which requires no pre-punched holes and only one-sided access. But there is a need for a relatively stiff counterpart, i.e. the preferred application is a sheet/profile joint. A nail-like fastener ("tack") is accelerated to high speed and driven into the parts to be joined. The speed, which can be controlled via the adjustable pressure, is optimised to suit material type and wall thickness.
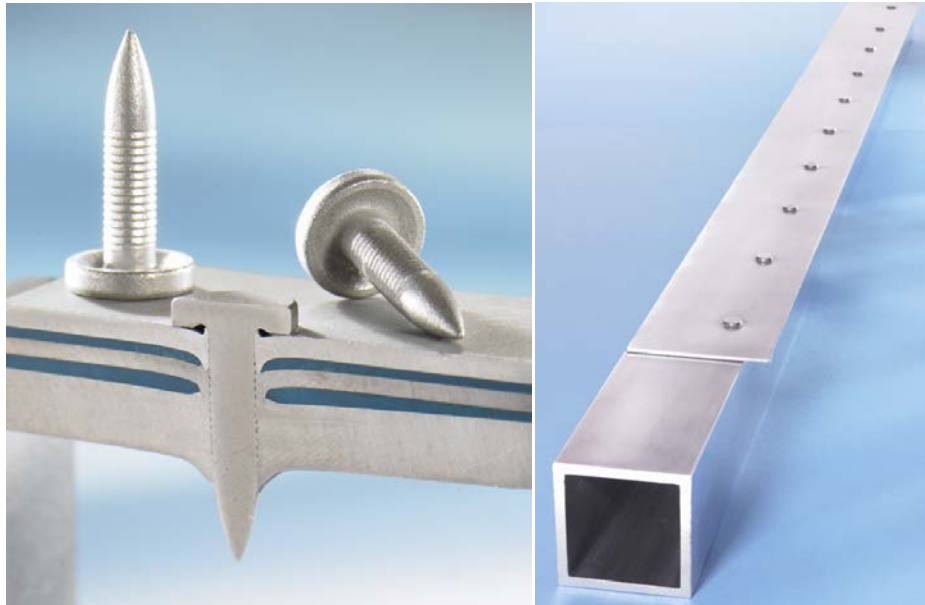
Three-layer aluminium profile joint with adhesive produced by RIVTAC° high-speed joining (left) and sheet-profile joint (right)

(Source: Böllhoff)

The ogival tip of the tack displaces the material without forming a slug, but leads to a momentary local temperature rise. The material flowing in the joining direction forms the draught whereas material flowing contrary to the joining direction flows into the knurled shaft of the tack and leads to a high form fit. Joint stability in the lower joint section is achieved by a combination force fit, resulting from the restoring force of the displaced material, and form fit.

4. Adhesive bonding

Adhesive bonding is a widely-established technique for joining metals, plastics, composites and other materials. It ensures uniform distribution and absorption of stress loads and enables the design of integrally sealed joints with smooth external surfaces.

However, exclusively bonded joints are, in general, not applied for structural purposes. They show only limited strength in peel and cleavage and thus, adhesive bonding is often combined with other joining methods.

4.1 Adhesive bonding process

Adhesive bonding uses a non-metallic substance which undergoes physical or chemical hardening ("curing") to produce a permanent joint between two surfaces.

The characteristics of an adhesively bonded joint are determined by the wetting behaviour of the surfaces to be joined, the bonding of the adhesive to the joined components and the inner strength of the adhesive. Different types of adhesives, pre-treatment methods and processing techniques are available. The selection of the optimum solution involves the consideration of multiple criteria and close contact with the respective suppliers is recommended. In some cases, extensive experimental testing may be required.

Robotic application of structural adhesive to aluminium sheet

Proper environmental control (temperature, humidity, cleanliness, ventilation, etc.) of the area where adhesive bonding is performed is important. Another basic limitation is that bonded joints must be supported until the adhesive has sufficiently cured. This can be achieved by temporary fixtures that ride along with the assembly processing. But in many cases, this task is fulfilled by another joining techniques which is already part of the overall assembly concept.

4.1.1   Type of adhesives

Adhesives are composed of polymers which are formed immediately before or during application of the adhesive. The applied polymers fall into two categories. Thermosets (e.g. unsaturated polyesters, epoxies, and polyurethanes) form permanent, heat-resistant, insoluble bonds that cannot be modified without degradation. Thermoplastics (e.g. polypropylene, polyamides, polyesters, acrylics, and cyanoacrylics) provide strong, durable adhesion at normal temperatures; for application, they are softened by heating without undergoing degradation. Elastomer-based adhesives (e.g. rubber, silicone) can function as either thermoplastics or thermosets.

Hot-melt adhesives

Hot-melt adhesives are based on thermoplastic polymers, they can be repeatedly heated to melt and cooled to solidify. They show good long term durability and resistance to moisture, chemicals, and oils, but their temperature resistance is limited and they tend to creep. They are primarily used in non-structural applications.

Structural adhesives

Structural adhesives must form and sustain a strong long-term bond between the adherents in varying environmental conditions. While for pure stiffening applications the modulus of the adhesive is the most important mechanical parameter, a combination of high modulus and high flexibility is essential for adhesives applied to improve crash performance.

Most structural bonding applications are based on thermosets (e.g. one/two-component epoxy or two-component polyurethane adhesives) which show good adhesion to a wide variety of substrates, excellent environmental resistance and withstand high-fatigue, high-toughness requirements. In specific cases, thermoplastics (e.g. light-curing acrylic adhesives or cyanoacrylates) that provide fast-setting times are used.

Pressure-sensitive adhesives

Pressure sensitive adhesives are typically formulated from natural rubber, certain synthetic rubbers, and poly-acrylates. Their special feature is that they do not solidify, but remain viscous. Bonds are made by bringing the adhesive film in contact with the substrate and applying pressure. The strength of pressure sensitive adhesives

decreases when the temperature is increased and they exhibit a tendency to undergo creep when subjected to loads. They are often used to temporarily hold components in position during assembly. Furthermore, roof linings and decorative trims may be bonded to the vehicle using adhesive strips.

Repair bonding

There is generally a lack of high temperature curing facilities in the repair shop. Thus, the selection of adhesives for structural repair is likely to be limited to two-part epoxy formulations, but with significantly reduced joint strength and performance compared with the original adhesive. This leads to relatively low strength repair bonds and, thus, structural bonding repairs should always be supplemented by mechanical reinforcements such as rivets, screws, clinches, etc.

In addition, the originally used aluminium surface pre-treatment techniques are generally not applicable. Special methods for local surface pre-treatment must be applied. It has been shown that certain two-part epoxy adhesives, used in conjunction with suitable in-situ cleaning/pre-treatment practices can provide a system with very good bond durability performance.

4.1.2   Design aspects

Joint design incorporating adhesives requires specific attention because of the large property differences between the adhesive and the materials being bonded. The bonded joint has different mechanical and thermal properties which, in addition, are influenced differently by temperature and other environmental conditions.

Adhesives perform best in shear, compression and tension, but poorly under peel and cleavage loading. The relatively low strength of the adhesive can be usually compensated by providing a larger contact surface. Also, an adhesive joint requires sufficient surface contact between the mating work pieces to allow for squeeze-out effects. The optimal joint design is therefore an overlap configuration of sufficient width. Butt joints are generally not applicable; certainly not for components with small wall thicknesses. Scarf joints would be better suited; however, they can be used only for large material thicknesses and are complicated to manufacture. The practical alternative is normally a (single or double) strap joint which is a combination of an overlap joint with a butt joint. In some cases, suitable measures can be already taken in the design of the individual components; e.g. when tongue and groove type bonded joints are considered, the cross section of an extruded aluminium profile can be properly adapted.
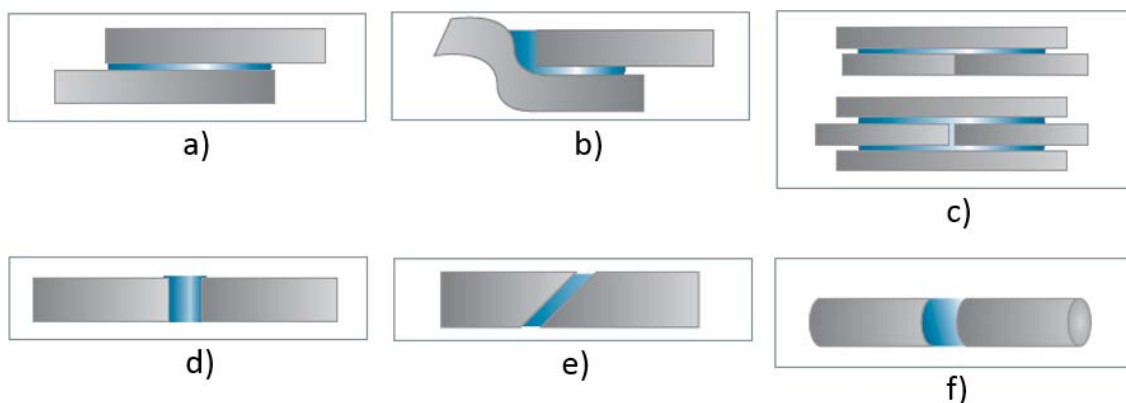
Types of adhesive joint design:
  a) Lap (overlap) joint, formed by partially placing one substrate over another
  b) Offset lap joint, similar to the lap joint
  c) Strap joint (single or double), a combination of an overlap and a butt joint
  d) Butt joint, formed by bonding two objects end to end
  e) Scarf joint (angular butt joint), cutting the joint at an angle increases the surface area
  f) Cylindrical joint, a butt joint between two cylindrical objects

(Source: Henkel)

4.1.3 Adhesive selection

It is essential that the selected adhesive fulfils all engineering and service requirements. Equally important is to consider whether the processing characteristics of the adhesive are compatible with the planned assembly process. The adhesive must be easy to handle, show good adhesion to the applied materials and sufficient fluidity to mould itself to their surface topography.

Since there is always the possibility of larger gaps between the flanges due to poor fit-up or misalignment, the adhesive must have sufficient gap bridging capability and the cured joint must offer consistent properties over a certain range of bond line thicknesses. Experience showed that there is very little property change over a bond line thickness range of 0.2 to 0.5 mm.

Furthermore, it must be taken into consideration that adhesive bonding is usually combined with a secondary joining method in structural joints. When combined with mechanical joining, the adhesive must still completely protect the flange because any open gap in the adhesive film will increase the corrosion risk. When combined with resistance spot welding, the adhesive may not interfere with the formation of the weld nugget. The adhesive must be fluid enough to flow out of the weld area without leaving significant residue that would weaken the weld, but it should not escape the joint area or contaminate the welding equipment.

4.1.4 Adhesive application and curing

Adhesive application and curing must be done in strict compliance with the manufacturer's rules. All fabrication parameters such as resin/hardener ratio, curing temperature, duration and pressure component fit up during adhesive curing, etc., must be properly controlled.

Application techniques

The optimum application technique depends on the selected adhesive and the specific production requirements. Adhesives are supplied as one- or two-part systems with viscosities ranging from thin liquids that can be sprayed to thixotropic pastes which must be pumped. Thus, they can flow into the bond line and fill any unevenness in the substrate surface or maintain the bead shape until a force is applied to fill the bond line.

Liquid gasket sealant adhesive robotically dispensed onto an aluminium cover

(Source: Henkel)

Manual application is generally limited to repair bonding and small series production. Typical handgun systems are cartridge-based or hose fed. In series production, the application of adhesives and sealants is usually a highly automated, repeatable process. Pneumatic or electric guns offer a variety of options for achieving precise, consistent dot and bead patterns. Optical quality assurance devices can be integrated, because apart from the dosing system also the type of the feeding unit and the programmed robot track may influence the resulting adhesive bead.

Adhesive curing

Structural adhesive bonds are generally cured by heating with negligible contraction. Curing is usually achieved with an oven, often concurrent with a paint bake cycle. Induction curing can be also applied either as a full cure or just enough to prevent any part movement during subsequent processing steps.

In specific cases, pre-curing may take place at ambient temperature as a result of mixing the two components or by contact with moisture. Other curing methods, e.g. curing with UV light, are relatively seldom used.

4.1.5 Surface pre-treatment for adhesive bonding

Ideally, the joining surfaces should be as clean and dry as possible (although adhesives are also often applied over stamping lubricants). Bonding to a naturally formed aluminium oxide surface layer generally does not provide the required long-term strength. If there is water or high air humidity in the service environment, the natural surface oxide must be replaced by a stable oxide layer formed under carefully controlled conditions.

The type and intensity of the surface treatment necessary for successful adhesive bonding depends on the materials to be bonded and the performance requirements of the bonded joint. Care must be taken to avoid contaminating the surfaces during or after pre-treatment.

Depending of the specific aluminium component, the applied surface pre-treatments may be somewhat different; however, the individual steps are essentially the same. Rolled aluminium products are often already surface pre-treated in the mill. Other product forms are normally surface treated by the supplier and delivered ready-for-assembly.

When a pressing lubricant is present on the material surface, the adhesive must be able to absorb and displace this layer before wetting the metal surface. Thus, the adhesive cannot be selected in isolation due to the complex interactions of the adhesive and the adherent surface, and possible lubricant interactions. The adhesive, pre-treatment and lubricant must be chosen as a fully compatible system.

Surface cleaning

Simple cleaning ("degreasing") removes surface oils and contaminants. In some cases, detergent solutions may suffice. More aggressive cleaning ("deoxidizing") requires an alkaline rinse, an acid rinse, or polyphenols followed by water rinsing. Metal removal is minimal, but the resulting bonding surface can be sufficient for moderately stressed joints in a dry environment.

Mechanical cleaning (e.g. brushing, grinding, sand or dry ice blasting) removes weak surface layers and enables a better interlock of the adhesive. However, the application of abrasive methods is not recommended since the resulting deformed surface layer may severely impair corrosion resistance. If necessary, operating under wet conditions can assist in the removal of contaminants and keeps dust generation to a minimum. A suitable abrasive cloth or water-proof abrasive paper should be used and the substrate must be thoroughly dried.

The preferred surface cleaning option is an alkaline or acidic cleaning/etching process which involves overt metal removal. Cleaning and etching may be two distinct steps or may be combined. After alkaline cleaning, an acidic cleaning step must always be carried out to remove the smut layer. For acidic cleaning, sulphuric acid or a mixture of sulphuric and hydrofluoric acid are often used. Additionally, nitric, nitric/hydrofluoric and phosphoric acids can be applied.

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

Conversion coating systems

Chemical conversion coating includes the removal of the natural oxide film and formation of a new, stable aluminium surface layer which improves adhesion of the adhesive and reduces the risk of corrosion.

Traditionally, chromate films were formed on the aluminium surface. Cr(VI) is, however, a highly toxic and carcinogenic substance; its use is now being restricted by legislation. In transport applications, chromium-free conversion treatments based on either titanium fluoride or a mixture of titanium and zirconium fluoride are widely used. Surface pre-treatment is carried out either by conventional immersion, spray or no-rinse processes. The resulting modified mixed oxide surface film is homogeneous, stable and offers good adhesion to organic compounds. Although the fluoride level in these conversion solutions is kept very low for health and safety reasons, its presence still presents a potential issue. Therefore, the recently developed fluor-free, environmentally friendly surface pre-treatment systems which are applicable for aluminium sheets, extrusions and castings are most interesting.
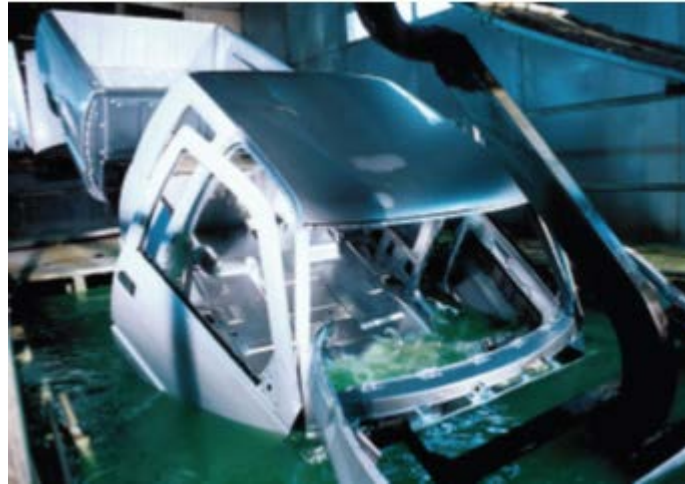
Light truck entering multi-metal pre-treatment immersion stage

(Source: Henkel)

Anodised films

Another possibility is to grow a controlled aluminium oxide film after electrolytic cleaning in an acidic bath. Thin anodised films (thickness 80 – 120 nm), highly suited for structural bonding in corrosive environments, are generated on aluminium sheets using an AC or DC powered electrolytic process. They consist of an amorphous barrier layer which improves the corrosion resistance of the material and a porous filament layer which provides excellent adhesion to adhesives. Suitable aluminium oxide films, ideal for low-viscosity adhesives in highly stressed applications, are produced by anodising in phosphoric acid. Sulphuric acid anodising can also be used, but the thicker oxide film reduces both adhesive strength and durability. They are best used with elastic adhesives for lightly stressed joints.

Conventionally anodized extrusions with thicker oxide films (≈ 10 μm) perform very well in bond durability, but special care must be taken to keep them dry. Anodized films are hygroscopic, but release water vapour during curing at elevated temperatures.

Primer coating

The main purpose of priming prior to adhesive bonding is to fill (seal) the surface when high-viscosity and/or fast setting adhesives are used. The organic coating must be applied after a suitable chemical pre-treatment step to ensure adequate primer adhesion and corrosion resistance.

4.1.7 Performance of adhesively bonded aluminium alloys

Detailed information about the inherent bulk mechanical and thermal properties of the adhesives is generally provided by the respective suppliers. But the bulk mechanical properties of adhesives do not represent the strength performance of a bonded joint.

Some shear strength data for adhesively bonded joints on specific surface pre-treatments may be also available. Typically, bond strengths are evaluated at ambient conditions and after exposure to high temperatures as well as high humidity and corrosive environments. Sometimes, the effect of the surface roughness of the substrate may

have been evaluated too. Furthermore, the durability of the various adhesives in different environments is generally known.

In practice, however, specially prepared test samples which run through the normal manufacturing process must be tested to determine the actual properties of adhesively bonded joints. Since there are no non-destructive methods for testing adhesively bonded joints, such test specimens are also used for quality assurance.

Mechanical characteristics of adhesively bonded joints

The mechanical performance depends on the actual bond strength, the joint design, and the environmental exposure conditions. There are different standardized destructive test methods, e.g. to determine the lap shear strength of boded joints or the peel resistance of adhesives.

The properties of an adhesive are strongly temperature-dependent. For many adhesives, the maximum temperature at which stressed bonded joints can be used is between 60 and 80 °C, higher heat resistance (up to 150 – 250 °C) may be achieved with heat-curing adhesives. Thus, when bonded joints are exposed to long-term tensile loads at elevated temperatures, application-specific tests will be often necessary to ensure that the creep strength of the applied adhesive meets the requirements.

Bonded joints are normally regarded as rather insensitive to vibration and fatigue at high frequencies. Nonetheless, mechanical loads and specific environmental conditions can exacerbate boundary layer problems. The simultaneous effects of temperature, environment and mechanical load may result in a significantly faster strength reduction than would occur if these three stresses operate individually.

Long-term durability of adhesively bonded joints

Since the mechanical properties of the adhesive are lower than those of aluminium alloys, it would be reasonable to assume that an adhesive bond on aluminium fails internally in the adhesive itself ("cohesive failure"). In practice, however, adhesive failure is often observed.

The most important environmental factors determining the durability of adhesive bonded aluminium joints are humidity, temperature and mechanical stress. Moderately increased temperatures and/or mechanical stresses have little adverse effect on a structural joint. The most severe environmental stress factor is water in its liquid or vapour phase. Water can enter the system by bulk diffusion through the adhesive, interfacial diffusion along the interface between the adhesive and substrate, and by capillary action through cracks or defects in the adhesive film or the aluminium oxide surface layer. Absorption of water may slowly plasticize and weaken the adhesive. Increasing temperatures and mechanical loads lead to an accelerated joint degradation. These effects are most important in confined areas where water and salt can accumulate for longer times and the micro-environment is much different from the open atmospheric conditions.

Water may also displace the adhesive at the interface and cause true interfacial failure. In addition, there is always the possibility that no adhesive is present over a certain flange length/area. In humid environments, such air pockets will eventually be replaced by (salty) water which causes chemical degradation of the adherent interface by corrosion of the metal. In addition, hydrolysis may weaken the oxide layer covering the aluminium substrate due to the formation of hydrated oxides. In addition, chemical reactions between water and specific components of the adhesive may form products that leach out and can react with the aluminium metal/oxide. All these effects intensify with increasing temperature and humidity.

Test methods for evaluating adhesive bond durability

In practice, long term performance of bonded joints cannot be reliably predicted from the properties of the adhesive and the adherent surfaces. The complexity of the interfacial chemistry generally requires experimental testing of the bonded structures.

Weathering tests of adhesively bonded aluminium include outdoor exposure (usually field tests under extreme climatic conditions) as well as accelerated testing under aggressive laboratory conditions. Actual driving tests require several years before an evaluation of the bond durability can be made. Therefore, great efforts have been made to develop short-term laboratory test procedures which allow reliable prediction of the long-term stability of adhesively bonded joints. Although it is difficult to use the results of laboratory tests to predict real life durability, a pre-treatment/adhesive system that performs well in accelerated tests provides a good starting point

for the design and manufacture of bonded joints. However, there is no harmonised specimen geometry and test procedure. Typical tests applied in practice are the VDA Cycle Test (VDA 621-415 standard) or the Salt Spray Test (DIN 50021, ASTM B117), but there are also OEM-specific test procedures.

4.2 Adhesive bonding in conjunction with mechanical joints

Normally, the adhesive is first applied to the one of the components being joined and the two items are placed together. A mechanical joint is made and the hardening of the adhesive layer completes the process. The applied adhesives are predominantly liquid adhesives like single component hot curing or two-component room temperature curing toughened epoxy adhesives.

Hem flange bonding

(Source: Fluidmetering)

The most common combined joining method is hem flange bonding of closure parts, but also spot-joints are widely-used.

Adhesive bonding and clinching

Clinch-bonding is used mainly for less demanding applications, e.g. to join steel to aluminium sheets in areas where the structural loads are relatively small.

Proper control of the clinching operation is necessary. There is a risk that "pockets" are formed when the liquid adhesive is squeezed out of the clinch point and the required clamping force cannot be achieved.

Adhesive bonding and self-piercing riveting

This combination developed to the predominant joining technology in the production of aluminium car body structures when using aluminium sheets. In an adhesively bonded joint, the rivets serve as peel stops and thus compensate for the adhesive's inherent shortcoming in peel performance. In contrast, the adhesive excels in shear performance. The net result is a joint that shows significantly improved shear strength and peel performance and a much better fatigue life.

The adhesive is pre-applied to the faying surfaces. When the self-piercing rivets are inserted, the adhesive is locally displaced. Thus, proper control is required in order to ensure that the squezzing out of the adhesive does not lead to local defects. Of specific importance is the avoidance of open channels to the seam edges since these could present serious corrosion problems.

Adhesive bonding combined with other mechanical fasteners

In principle, for improved joint performance, all types of mechanical fasteners can be combined with adhesive bonding. Of specific interest is the preliminary fixation of an assembled bonded structure during the cure of the adhesive, e.g. by blind rivets, threaded fasteners or tack high-speed joining.
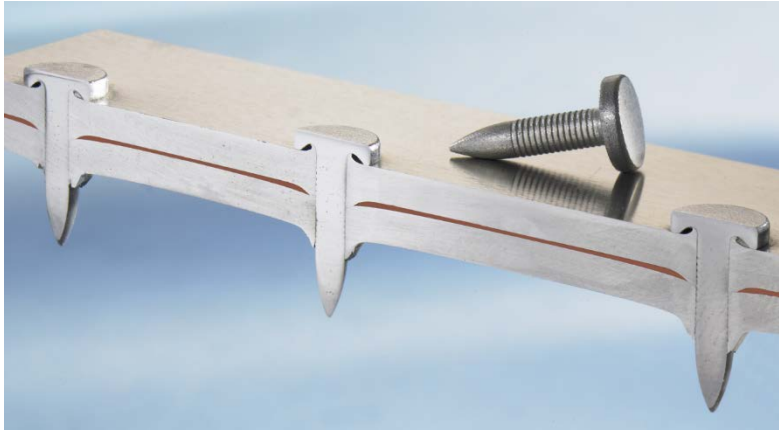
Aluminium-hybrid joint produced in RIVTAC® high-speed joining

(Source: Boellhoff)

4.3 Combination of adhesive bonding and welding

Potential degradation of the adhesive by the high heat input limits the possibilities to combine adhesive bonding with fusion welding. Nevertheless, the combination of adhesive bonding and spot or seam welding (e.g. by resistance spot welding, friction stir spot welding or laser welding) offers interesting possibilities.

Practically applied is the combination of adhesive bonding and resistance spot welding ("WeldBonding"). The weld-bonding process is generally fully automated and utilises robotic dispensing systems. The standard joint configuration (overlapping sheets) is highly suited for both joining processes. Before the actual spot welding process starts, the electrode force displaces the adhesive to obtain electrical contact between the sheets and the weld can be made in the normal way. Local heating generated during spot welding causes only a limited damage around the weld. The adhesive is finally cured to complete the assembly.

The surface condition (or prior surface treatment) of the aluminium sheets must be properly selected to ensure the long-time durability of the adhesive, but not to interfere with the spot welding process. Also, health and safety issues linked to the use of adhesives need to be considered.