

EAA Aluminium Automotive Manual – Joining

11. Joining dissimilar materials

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11.0 Introduction

As aluminium alloys are more frequently applied in the automotive industry, the joining of aluminium to itself, but in particular also to other materials becomes increasingly important. When joining aluminium to other materials, three different tasks can be differentiated:

- Joining aluminium to compatible metals (with some degree of solubility in each other)
- Joining aluminium to incompatible metals (little or no solubility in each other)
- Joining aluminium to different types of material (e.g. plastics and composites, ceramics).

Joining dissimilar materials is generally more difficult than joining the same material (or alloys with minor differences in composition) and the number of applicable joining techniques decreases. However, in most cases, dissimilar materials can be successfully joined using an appropriate joining method and properly adapted processing conditions.

Applicable joining processes for aluminium to other metals may be:

- Fusion arc welding processes
- Other fusion welding processes (beam welding, resistance welding)
- Solid-state joining processes
- Brazing and soldering
- Mechanical joining processes
- Adhesive bonding.

However, when aluminium must be joined to other types of materials, e.g. plastics and composites as well as ceramics, fusion welding methods cannot be applied.

Some of the processes described in the previous sections can be applied to join dissimilar materials with little adaptations. They will not be covered in detail in this section. The main focus will be on processes which have been specifically developed or modified to fulfil the additional requirements.

A basic rule is that there is not a single process or a set of processing parameters which is best for all material combinations or fits all performance requirements. Each process has its advantages and limitations. Thus each dissimilar material joint is best viewed as a special application with unique requirements. Furthermore, many of the new developments are still in the laboratory or pilot-plant stage and not yet approved for large series application. Often extensive qualification tests may be necessary and time will show which joining techniques will be most successful for joining specific material combinations.

11.1 General issues and limitations

A number of factors must be taken into consideration when designing a dissimilar material joint, including:

- Material combination and performance requirements
- Joint design and material thicknesses
- Thermal expansion-contraction mismatch during joining and in service
- Potential for galvanic corrosion problems in service
- Fixturing requirements and constraints regarding joining stresses.

Depending on the specific joining process, additional factors have to be considered as well, e.g. in case of fusion welding:

- Differences in melting temperature
- Formation of brittle intermetallic compounds during joining which may lead to brittle joints
- Heating and cooling rate effects on the microstructure of the joint
- Need for pre- and post-heating to minimize stresses during welding and cooling
- Need for composite transition materials or special filler materials during joining.

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With respect to the automotive market, the most important task is joining aluminium to steel. Consequently, this problem is also the main driving force to develop new, improved joining methods for dissimilar materials. Most examples will therefore cover the aluminium-steel system. But the wish to produce innovative lightweight products has also raised significant interest in the production of structural joints between aluminium and plastics as well as carbon fibre reinforced composites. On the other hand, joining aluminium to ceramics is rather used in niche applications.

11.1.1 Metallurgical limitations

The following table shows the ease of joining aluminium to other metals by fusion welding processes. It indicates that aluminium is, in general, difficult to weld to other materials. For this reason, joining of aluminium to other metals has been mainly done using other joining methods than fusion welding in the past (in particular mechanical joining and adhesive bonding). However, new developments have led to a renewed interest in fusion welding processes.

	W	Ta	Mo	Cr	Co	Ti	Be	Fe	Pt	Ni	Pd	Cu	Au	Ag	Mg	Al	Zn	Cd	Pb	Sn
Al	Red	Red	Red	Red	Yellow	Yellow	Red	Yellow	Red	Yellow	Red	Yellow	Yellow	Yellow	Yellow	Green	Yellow	Red	Red	Red

Legend: ■ Excellent, ■ Good, ■ Fair, ■ Poor

Fusion welding performance of aluminium to other metals

When joining aluminium to other metals, the major difficulty is that at high temperatures, and in particular in the presence of a liquid phase, brittle intermetallic compounds are formed at the interface which result in poor joint characteristics. As an example, fusion welding of aluminium to steel leads to the formation of particles of intermetallic phases such as FeAl_2 and Fe_2Al_5 . Brittle intermetallic phases are also formed when “fair weldable” metals such as copper, magnesium or titanium are directly fusion welded to aluminium.

11.1.2 Galvanic corrosion

Galvanic corrosion is an electrochemical process in which one metal corrodes preferentially to the other. Both metals must be in electrical contact in the presence of an electrolyte. Dissimilar electrically conductive materials have different electrode potential and when two or more come into contact in an electrolyte, one material can act as anode and the other as cathode. The difference in electrode potential between the dissimilar metals is the driving force for an accelerated corrosion attack on the anode member of the galvanic couple. The anode metal dissolves into the electrolyte, and the corrosion products deposit on the cathode.

There are several possibilities to reduce or even prevent this type of corrosion:

- The easiest option is the electrical insulation of the two materials from each other. If they are not in electrical contact, no galvanic couple will develop. This can be achieved by using non-conductive materials between metals of different electrode potential.
- The prevention of contact with an electrolyte can be done by using water-repellent compounds (such as greases) or by coating the metals with an impermeable protective layer (e.g. a suitable paint, varnish or plastic). If it is not possible to coat both materials, the coating should be applied to the material with the higher electrode potential. If the coating would be applied only on the more active material, there will be a large cathodic area if the coating is damaged and for the exposed, very small anodic area, the corrosion rate will be correspondingly high.
- Electroplating or other metallic coatings can also help. More noble metals are generally used since they resist corrosion better. Galvanizing with zinc protects the steel base metal by sacrificial anodic action.

- Cathodic protection uses one or more sacrificial anodes made of a more active metal than the protected metal. Alloys of metals commonly used for sacrificial anodes include zinc, magnesium and specific aluminium alloys.
- Cathodic protection can also be achieved by connecting a direct current (DC) electrical power supply to oppose the corrosive galvanic current.

11.1.3 Thermal expansion

Thermal expansion is the tendency of matter to a volume change in response to a temperature change. For solids, the main concern is the change along a length or over some area. The coefficient of thermal expansion is a material-specific parameter and generally varies with temperature. However, common engineering solids usually have coefficients of thermal expansion that do not vary significantly over the range of temperatures where they are designed to be used, thus practical calculations can be based on an average value of the coefficient of expansion.

When the applied joining technique involves significant temperature changes, thermal expansion effects must be considered already during the joining operation of dissimilar materials. In addition, also the impact of temperature changes in the service phase must be taken into account. For body-in-white applications, however, the most important post-joining effect is the lacquer bake hardening process which takes place at temperatures up to about 180°C.

11.2 Joining aluminium to other metals

Most of the technologies that have been used to join dissimilar metals in the past (e.g. mechanical joining processes, solid state joining techniques, adhesive bonding) are only able to deal with certain geometries or require extensive control inputs. Thus there is a big interest in the introduction of more flexible joining techniques in industrial practice.

The most critical factor when joining aluminium to other metals (including steel) are the metallurgical issues. Under the influence of heat, intermetallic phases are formed at the interface between the two materials either during solidification of the molten mixture or by diffusion processes at the interface. The more heat is applied, the larger the zone containing the intermetallic phases and the poorer the mechanical properties of the joint.

However, the different chemical and physical properties also require appropriate measures to be taken. Differences in the thermal expansion coefficients of the two materials may create a stress field around the joint. There may be also a marked tendency for corrosion as a result of the difference in electrochemical potential.

Most examples described below include aluminium/steel joints. However, the basic process principles can be also applied to joints of aluminium with most other non-ferrous metals. Because of its importance in lightweight design, a specific chapter is only added for aluminium/magnesium joints.

11.2.1 Fusion arc welding processes

The two most common methods which enable the application of arc welding processes for joining aluminium to steel are the use of bimetallic transition inserts and the application of a suitable coating to one of the metals prior to welding. More promising, however, are recent efforts to limit the heat input in fusion welding to the absolutely necessary minimum in order to closely control the formation of intermetallic phases. Today, the Cold Metal Transfer (CMT[®]) welding technology is industrially applied to join aluminium and steel sheets in automotive applications.

11.2.1.1 Fusion welding with transition inserts

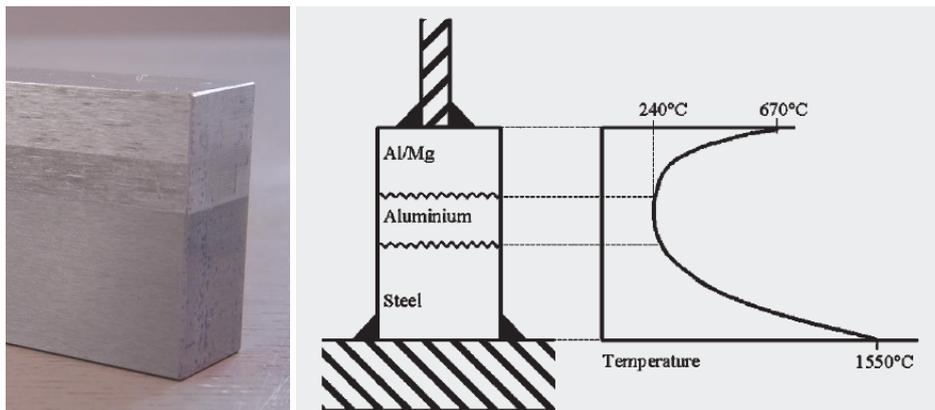
The use of bimetallic transition inserts is today widely employed in the shipbuilding industry. The application of bimetallic transition inserts means that similar material joints can be made

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on either side of the insert (i.e. one side of the insert is a steel-to-steel and the other an aluminium-to-aluminium joint). Thus standard arc welding methods can be used. However, care must be taken to avoid overheating the inserts during welding since this may cause growth of brittle intermetallic compounds at the interface of the transition inserts.

Aluminium/steel transition joints are applied only for special cases in the automotive sector. The primary requirement is to keep the heat input sufficiently low to restrict the time above temperatures of about 300 °C and thus minimise the formation of brittle intermetallic phases. It is good practice to perform the aluminium-to-aluminium weld first. This way, a larger heat sink can be provided when the steel-to-steel weld is performed.

Bimetallic transition materials combining aluminium with different other materials as steel, stainless steel and copper are commercially available. The methods used for joining the dissimilar materials - and thus producing the bimetallic transition inserts - are usually solid state joining processes (e.g. roll bonding, explosion welding, friction welding or hot pressure welding).

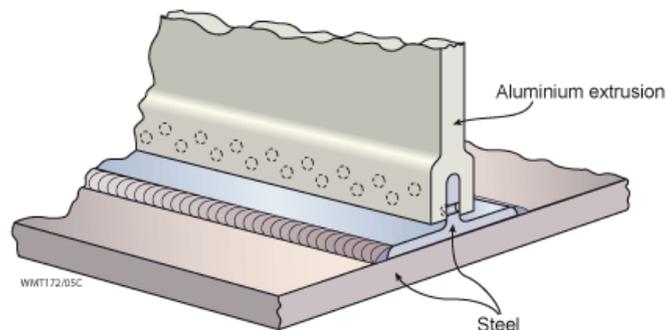


Welding of dissimilar metals with transition joints

(Source: Shockwave Metalworking Technologies)

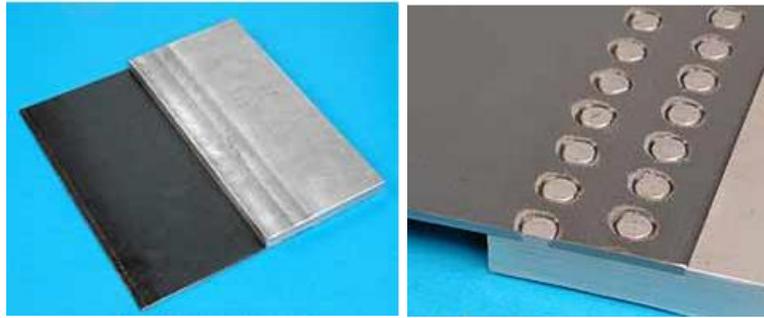
As an example, a transition insert for aluminium/steel (Triplate®) welding produced by explosion welding is shown above. It consists of a sandwich of three metals (steel, EN AW-1050A and EN AW-5083).

Another type of transition joints has been developed at TWI. The Stir-lock™ technique is a forge/forming seam joining technique. One side of the Stir-lock™ joint can be compared with riveting. A rivet head is formed into a countersunk hole, to provide a mechanical interlock between two or more plates. The countersunk holes are made in the harder sheet material. The material that forms the interlock (or “rivet head”) remains an integral part of the softer, more easily formable sheet.



Possible application of the Stir-lock™ technique for joining dissimilar metals

(Source: TWI)



Single sided, Stir-lock™ aluminium-to-steel transition joint: Friction treated side (left) with a continuous weld track and opposite side showing aluminium extruded into the pre-machined holes (right)

(Source: TWI)

11.2.1.2 Fusion welding of coated materials prior to welding

Another option is the application of fairly thick aluminium coatings to the other material. Different methods can be used to coat steel with aluminium, e.g. roll bonding, dip coating (hot dip aluminizing) or brazing an aluminium sheet to the steel surface. Once coated, the steel member can be arc welded to the aluminium component. Care must be taken to prevent the arc from impinging onto the steel. Proper processing includes directing the arc onto the aluminium member and to allow the molten aluminium from the weld pool to flow onto the aluminium coated steel.

Another method of joining aluminium to steel involves coating the steel surface with silver solder. The joint is then welded using an aluminium filler alloy, taking care not to burn through the barrier layer of silver solder.

Neither of these coating methods can ensure full mechanical strength of the joint; they are usually used for sealing purposes only.

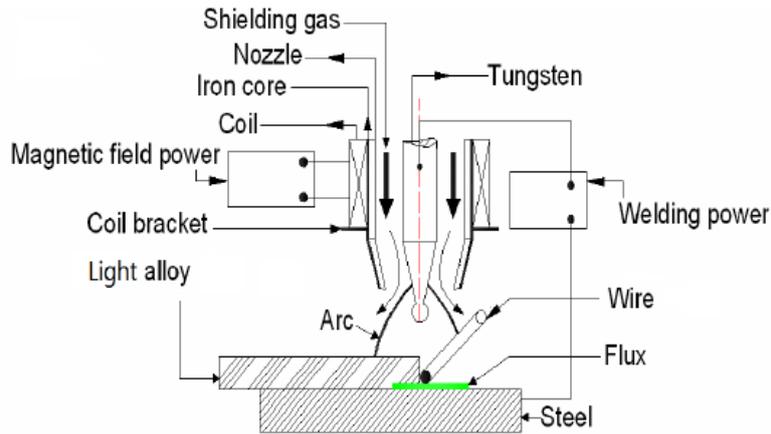
11.2.1.3 Fusion-brazing arc welding processes

In the fusion-brazing welding process, the aluminium base metal and the filler metal melt and form a fusion weld, whereas the molten aluminium alloy spreads on the top surface of the steel plate and forms the brazed joint with steel. As the steel does not melt, the excessive formation of the intermetallic compounds can be effectively prevented. The heat source used in brazing-fusion welding of aluminium to steel can be a MIG arc or a TIG arc. But also electron beams or laser beams can be used for this purpose (see 11.2.2.1).

In fusion-brazing welding, a properly controlled, stable energy input is necessary to make sure that the steel does not melt. Arc welding has the advantage of low cost, but its power output is normally not sufficiently stable and the welding efficiency is not satisfactory keeping in mind the increasing application requirements. Some progress could be achieved using the pulsed MIG welding technique (see 3.1.3.2). Better results were achieved by the application of the Laser MIG hybrid technique (see 10.3.1.4). However, up to now, only aluminium/steel joints produced by the cold metal transfer (CMT®) welding process have found practical application in the automotive industry.

a) Arc brazing-welding

As an example, butt brazing-welding was carried out between an aluminium alloy and stainless steel with the help of a TIG arc using an Al - 6 % Cu filler alloy and a non-corrosive flux. On the aluminium side, the interface shows the characteristics of a welded joint whereas on the steel side, the interface characteristics are that of a brazed joint.



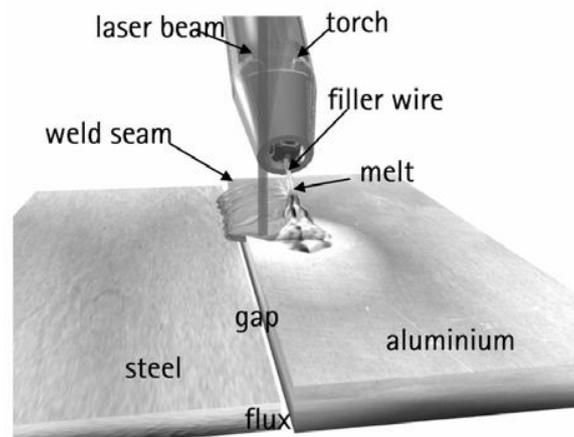
Electromagnetic hybrid TIG welding-brazing

(Source: J.Luo et al.)

A thin intermetallic compound layer formed at the interface between the weld seam and the steel with an average thickness of 3 – 5 μm (which is less than the generally accepted limiting value of 10 μm). The dominating factor determining the joint quality is the wetting action on the steel side (i.e. the spreading performance of the liquid filler wire). Further improvements could be achieved using a longitudinal electromagnetic hybrid TIG welding-brazing method on an aluminium alloy/low carbon steel joint. The distribution of the second phase particles in the welding seam was more uniform and the grain size is much smaller than in a normal TIG brazing weld seam.

b) Laser MIG (or TIG) hybrid joining

In a first attempt, a large spot laser was used to stabilize the MIG welding process and maintain a constant MIG arc energy output. In addition, the leading large spot laser preheats (but does not melt) the galvanized steel and thus improves the spreading of the liquid aluminium alloy on the steel top surface in case of overlap joints. The MIG arc energy (which is the main heat input) is used to melt the filler metal and the aluminium base metal; the laser energy plays a secondary role in brazing-fusion welding. Similarly, laser TIG hybrid welding (see 10.3.1.2) can also be used. Whereas dissimilar metal joints could not be produced in laser or arc welding only, acceptable joints without obvious defects were obtained using the laser-assisted hybrid processes with a relatively wide processing window.

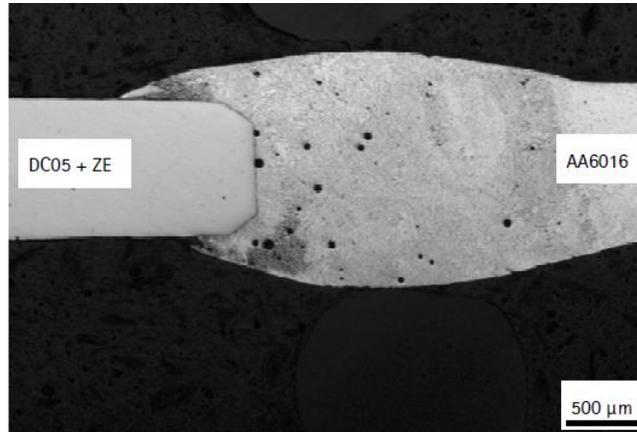


Principle of the laser MIG hybrid joining process

(Source: C. Thomy and F. Vollertsen, BIAS)

Using laser MIG hybrid welding, aluminium/steel joints for both structural as well as tailored blank applications have been produced successfully in the laboratory. The aluminium and the steel sheet were arranged in a butt joint configuration. In this case, the laser beam was positioned on the aluminium side. During joining, the edge of the aluminium sheet is molten -

and together with the molten filler wire - the gap between the aluminium and the steel is bridged and the steel is wetted by the aluminium melt. The main task of the MIG arc is to create a large molten melt pool and to supply filler material to the melt pool. The laser beam, which is operated in the keyhole mode, allows to increase the welding speed by stabilising the MIG arc. Thus, heat input is reduced and the negative effects of a too large heat input such as excessive phase layer formation and distortion are avoided.



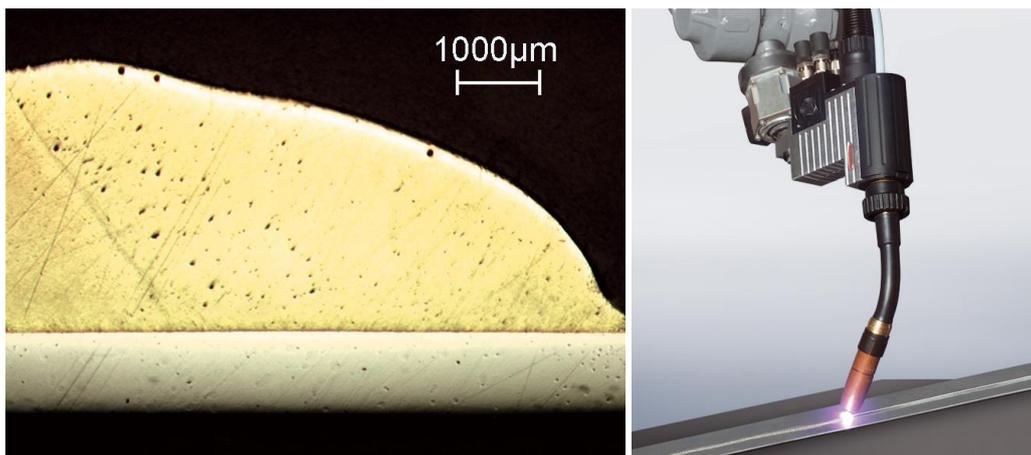
Laser MIG hybrid welded joint between EN AW-6016 to zinc coated DC05 steel sheet

(Source: C. Thomy and F. Vollertsen, BIAS)

c) Cold metal transfer (CMT®) welding

The principle of the cold metal transfer process is described in detail in section 3.1.3.6. This process is commercially used both in car body assembly as well as for the production of aluminium/steel tailored blanks.

The CMT® process evolved from the continuous adaptation of the MIG process to resolve the problems posed by the joining of steel and aluminium. It allows the material transfer to take place with barely any flow of current. The aluminium base material melts together with the aluminium filler, with the melt wetting the galvanised steel. Although the steel base material is only wetted during this brazing process and does not melt, fracture always occurred in the aluminium base material, not in the weld seam.



Cold metal transfer (CMT®) welding of aluminium to galvanised steel

(Source: Fronius)

The special gas-shielded cold metal transfer process fulfils the crucial requirements of a joining process for dissimilar metals: low thermal input and good controllability. When steel is joined to aluminium, the filler metal and the aluminium wet the galvanised steel sheet and the filler metal fuses with the aluminium. On the steel side, a brazed joint is obtained, which the aluminium is then welded against. A special aluminium filler metal (Al - 3 % Si - 1 % Mn) has been developed for braze-welding.



Steel-aluminium hybrid blank
(Source: voestalpine Europlatinen)

11.2.2 Other fusion welding processes (beam welding, resistance welding)

A more detailed evaluation of resistance spot welding (see 5.1) to join aluminium to steel was an obvious step keeping in mind the widespread use of this joining process in the automotive industry. However, as shown below, little success was achieved in laboratory tests.

Laser (and electron) beam welding offer the possibility of a closely controlled, localized heat input and thus may allow better control of the formation of brittle intermetallic phases at the interface. Practical tests were successful, but no series application are known today. Electron beam welding techniques have been applied with some success in industrial tests, however, the following considerations will be limited to laser beam welding.

11.2.2.1 Joining of aluminium to steel with lasers

Experimental tests using keyhole laser welding (see 4.1.2.2) in order to join aluminium to steel have been carried out, but with limited success. Some approaches to decrease the thickness of the layer of intermetallic phases which are formed during laser welding at the aluminium/steel interface are described in the scientific literature. The results achieved up to now using different laser welding configurations and a wide range of processing conditions are not convincing. The tests in the keyhole welding mode using a steel-on-aluminium overlap configuration showed that changes of the processing parameters which decrease the percentage of intermetallic components also cause unfavourable effects such as inadequate penetration depth, spattering and cavity formation.

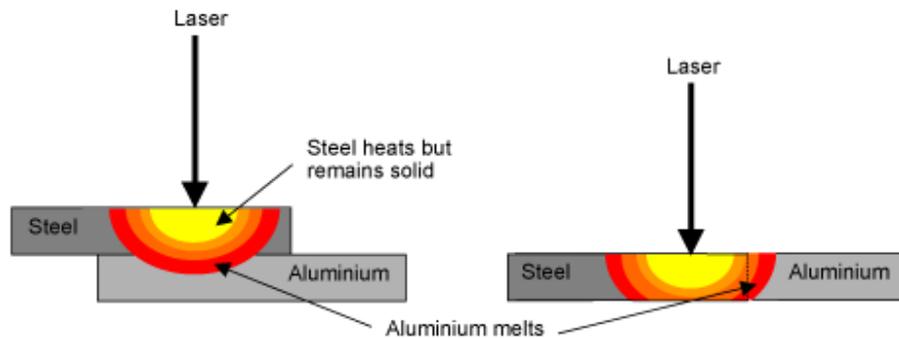
On the other hand, laboratory tests using conduction laser welding (see 4.1.2.1) have shown very promising results. The advantage of using the conduction laser welding method to join dissimilar materials is based on the high process stability which allows a better control of the temperature in the interaction area between aluminium and steel.

a) Laser conduction welding

A possible approach based on the conduction welding principle is the use of a defocused laser beam which is directed onto the steel sheet; causing local heating, but no melting. Heat is conducted through the steel and causes local melting of the adjacent aluminium. The molten aluminium wets the steel and then solidifies, resulting in a metallic bond. The process can be applied to both lap joints and butt joints, although it is most suited to lap joints. In practice, the difficulty is to control heat input so that melting of steel is more or less prevented. However, even when a small amount of local melting of the steel sheet does take place, a relatively strong bond is formed when the intermetallic transition zone is sufficiently small.

The technique was used to join Zn-coated steel sheets typically used in automotive body-in-white fabrication to aluminium sheets. Some intermetallic phases were formed at the interface, but the use of adequate process control measures ensures that the intermetallic particles do not significantly influence joint strength.

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Schematic of the laser joining process for both lap and butt joints

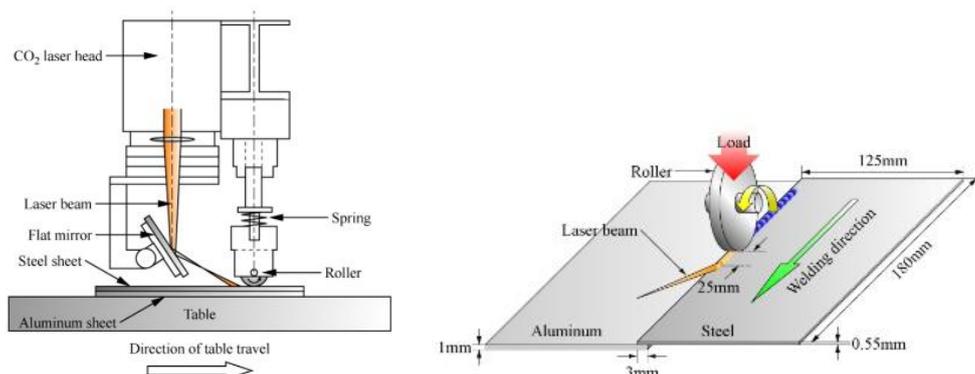
(Source: TWI)

Overlap welds can be made best using steel on top and aluminium at the bottom. This configuration results in a better joint quality mainly due to the thermal characteristics of both materials. When aluminium is used on top, the higher thermal conductivity of aluminium results in a much larger affected interfacial area since the heat tends to flow along the interface in the aluminium part rather than heating the steel. When steel is used on top, the conduction of heat from steel to aluminium can be much better controlled.

b) Laser roll welding process

The laser roll welding process was developed in 2002. The basic idea was to exploit the high local heat input and short process time of laser welding to shorten the thermal cycle in order to control the formation and growth of the brittle intermetallic phases. Furthermore, good thermal contact and rapid heat transfer from the steel sheet to the aluminium alloy sheet should be ensured by a pressure roller.

Tests have been carried out using zinc coated steel and an aluminium alloy sheet. A layer of intermetallic compounds was observed in all welded joints. However, when the thickness of the intermetallic particles was less than 10 μm , tensile test specimens failed in the base metal (i.e. the damaging effect of the brittle intermetallic compounds can be tolerated). The welding speed influences the joint performance (intermetallic phase layer thickness and tensile shear strength) to a greater degree than the roll pressure.



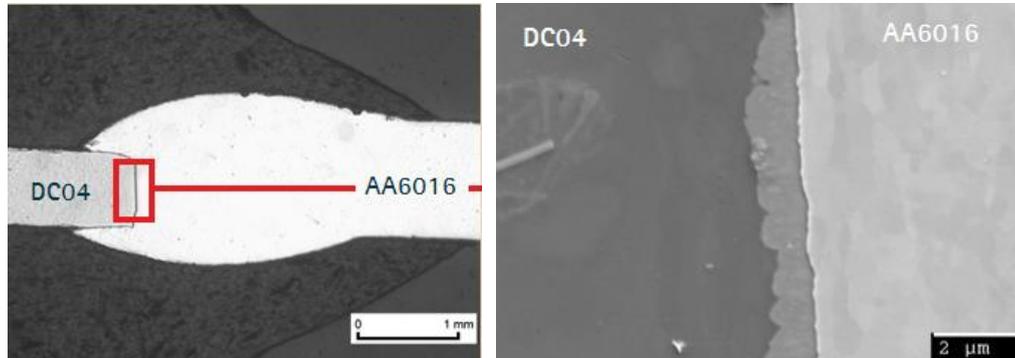
Schematic diagram of the Laser Roll Welding process

(Source: M. Kutsuna et al.)

This method was further developed to produce cold-formable aluminium-steel hybrid blanks. The aluminium and the steel sheets converge with an overlap of 5-10 mm and are guided between the rolls of a modified cold mill. One of the joining rolls is grooved, so that the roll forces mainly act on the overlapping area. The joining zone is activated and heated by means of a laser, immediately before undergoing the cold-rolling pass.

c) Laser welding-brazing process

Preliminary tests using a high-power semiconductor laser showed that welding-brazing of aluminium to steel is possible. As an example, an aluminium/steel butt joint is shown below. Aluminium/steel joints can be made with both CO₂ and solid state lasers using an AlSi12 filler wire and directing the laser spot primarily onto the aluminium alloy sheet. However, relatively large and brittle intermetallic phases are formed in the transition zone.

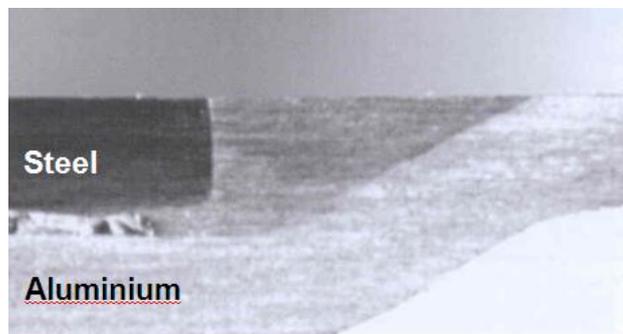


Laser welded aluminium/steel butt joint

(Source: BIAS)

The use of a brazing flux (Nocolok® brazing flux) led to some improvement. The specimens were overlapped and while the brazing filler (EN AW-4043) was supplied to the lapped corner. The flux improved the wettability of the brazing filler metal and increased the brazing width. It also restrained the formation of a layer of Fe-Al intermetallic phases at the joint interface. However, the use of flux involves the application of a flux coating before brazing and the removal of residual flux after brazing, which tends to reduce work efficiency and productivity.

Even better results were achieved when a Zn-based brazing wire was used in combination with a Zn-coated steel.



Laser brazed aluminium/steel joint using Zn-based brazing wire and non-corrosive flux

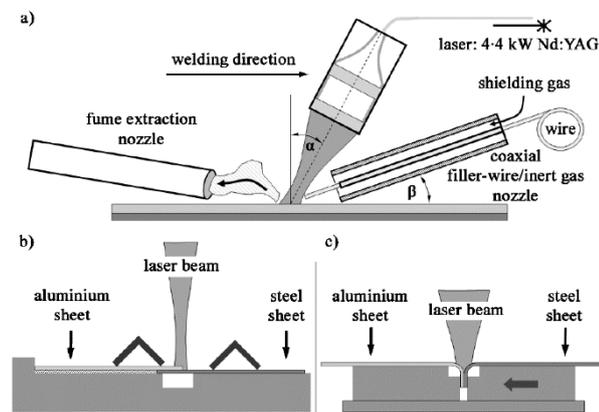
(Source: Novelis)

Further developments led to the realisation of flux-less laser welding-brazing joints. Using an AlSi12 filler wire, a normal weld is produced between the filler wire and the aluminium substrate. Subsequently, the molten filler metal wets the steel and creates a brazed joint on the steel side. The preferred joint configuration for “Fluxless Laser Brazing” is a T joint, but also overlap joints can be realized. Both hot dip and electro galvanised steel sheets can be joined with this brazing method. Favourable results are achieved up to a brazing speed of 4 m/min.



Principle of the “Fluxless Laser Brazing”
(Source: Aleris)

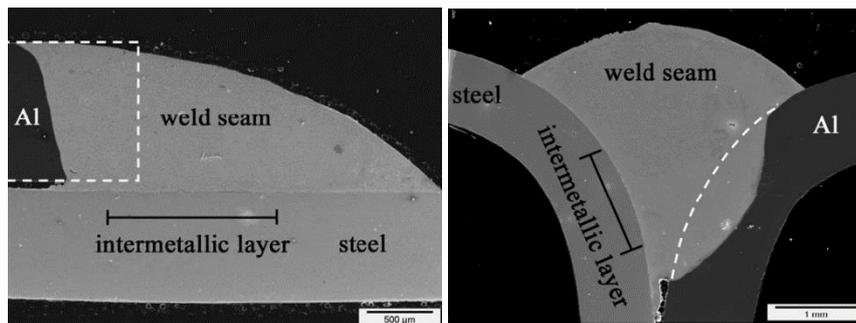
For flux-less laser welding-brazing of an aluminium alloy sheet to a galvanized (zinc coated) steel sheet steel, the application of a zinc-based filler alloy (Zn – 2 wt. % Al) produced better results than an Al-based wire. The reason is the use of similar materials for the zinc coating and the filler wire as well as the high miscibility of aluminium in zinc.



Laser welding-brazing process

(Source: H.Laukant et al., Science & Technology of Welding and Joining, 10 (2005) 219)

For the filled overlap weld geometry, the laser beam was directed at the aluminium sheet. Hence the composition of the formed weld seam is aluminium-rich. In case of the filled flange geometry, the laser is positioned between the two flanges and a smaller amount of the aluminium sheet is melted. In both geometries, the intermetallic layers are limited to a small area where the laser transfers the highest energy into the steel. The intermetallic layers exhibit a maximum thickness of 5 μm , i.e. the mechanical characteristics of the joints exhibit tensile strength values of up to 80 % and an elongation of 40 % in relation to the used aluminium base material (EN AW-6016, T6).



Laser welding-brazing joints: filled overlap (left) and filled flange geometry (right)
 (Source: H.Laukant et al., *Science & Technology of Welding and Joining*, 10 (2005) 219)

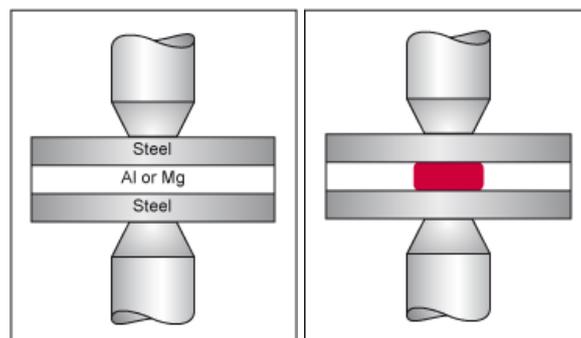
The key advantage of this process is the freedom to select laser power, brazing speed and filler wire speed independently from one another. In analogy to the use of a laser beam, such a brazing process could also be made using an electron beam.

11.2.2.2 Resistance spot welding for joining steel to aluminium

When the standard resistance spot welding technique is used to join steel and aluminium alloy sheets, the very brittle intermetallic phases which are produced at the interface significantly decrease joint strength.

A possible solution offers a hot dip aluminized steel sheet which was developed by Kobe Steel and Nissan Steel specifically for joining to aluminium using conventional welding equipment. It has a nitrogen-rich layer at the interface of the base steel to the aluminium coating layer which effectively prevents the inter-diffusion of iron and aluminium atoms, i.e. the formation of brittle intermetallic phases at the interface is prevented. The resultant joint strength is almost equivalent to that of a resistance spot welded aluminium/aluminium joint.

In another approach to overcome the brittle intermetallic phase problem by technological means, aluminium (and magnesium) were resistance spot welded to steel in a triple layer lap joint configuration with steel sheets on both sides. During welding, the current and electrode force in the spot welding operation were controlled so that the heat (generated mostly within the steel) was sufficient to melt the aluminium (or magnesium) sheet. It was expected that the molten metal, contained by the electrode force, would wet the steel surface, forming a bond at the interface between the two materials.

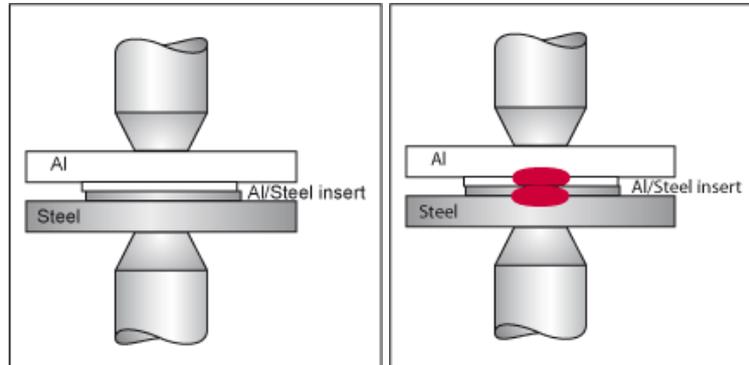


Joining aluminium (or magnesium) to steel by resistance heating
 (Source: TWI)

Experimental tests with different electrode forces and welding currents indicated that it was possible to produce some bonding in the interface between the steel and magnesium alloy. However, bonding could only be achieved when the welding current was adjusted to melt only the central magnesium sheet at a pre-set electrode force. Furthermore, severe porosity and solidification cracking occurred in the centre of the nugget and the welds exhibited weak, brittle interface failures in peel testing. When the same approach was used to join aluminium to steel, a continuous layer of intermetallic phases was formed at the interface since a steel

surface layer also melted. The weld failed in a weak, brittle manner at the interface on peel testing.

In a second set of experiments, aluminium was joined to steel using an aluminium/steel transition piece. In this case, a weld nugget formed on the steel side as in conventional resistance spot welding. The generated heat also melts the aluminium at the interface of the transition piece to the outer aluminium sheet.



Resistance spot welding of aluminium to steel using a transition material

(Source: TWI)

The heat sink effect of the aluminium within the joint prevents the steel from melting completely through to the contact with the aluminium. However, shrinkage defects were observed at the steel interface since that part of the nugget solidifies last. In addition, intermetallic phases are formed at the interface within the transition piece. Consequently, the resulting joints failed on peel testing in a brittle manner by pulling a plug out of the thin aluminium layer of the transition material. Nevertheless, some joint strength could be achieved.

11.2.3 Solid-state joining processes

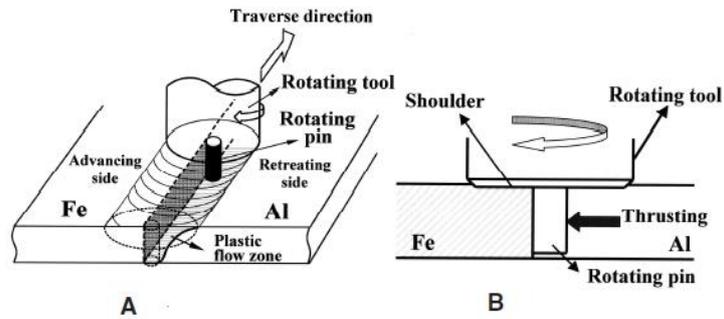
Solid-state joining processes are generally well suited to join dissimilar metals. Friction welding processes such as rotational friction welding (see 7.1.1.1), friction stud welding (see 7.1.4), etc., ultrasonic welding (see 7.3) and electromagnetic pulse welding (see 7.2.4) are routinely used to manufacture specific automotive components.

Therefore in the following, only some new developments in connection with the friction stir welding technology will be covered in more detail.

11.2.3.1 Friction stir welding

Linear friction stir welding (see section 7.1.2.1) can be used to join aluminium to steel. The rotating pin is plunged into the aluminium. Then, the rotating pin is pushed toward the faying steel surface and the oxide film is mechanically removed from the faying surface by the rubbing motion of the rotating pin. Aluminium, which is in a plasticized state due to the heat generated by the friction of the rotating tool shoulder, consequently adheres to the activated faying steel surface, i.e. a joint between steel and aluminium is achieved.

Since the rotating pin is plunged into the softer aluminium and does not come in contact with the steel, the rotating pin shows minimal wear. When the rotating pin was inserted in the standard position (around the centre of the interface), no joint could be produced due to excessive wear of the rotating pin.



Schematic of the rotating pin position

(Source: K. Kimapong and T. Watanabe)

No intermetallic compounds were observed at the interface between the steel and the aluminium alloy. However, some intermetallic compounds were observed in the upper region of the friction stir weld where the temperature is higher due to the additional heat generated by the rotating tool shoulder.

11.2.3.2 Friction stir welding

Variants of the friction stir spot welding technology (see section 7.1.3.1) are well suited to join aluminium and steel. It was first used in closure applications in 2005 to join the trunk lid and bolt retainer for the Mazda MX-5 sports car.

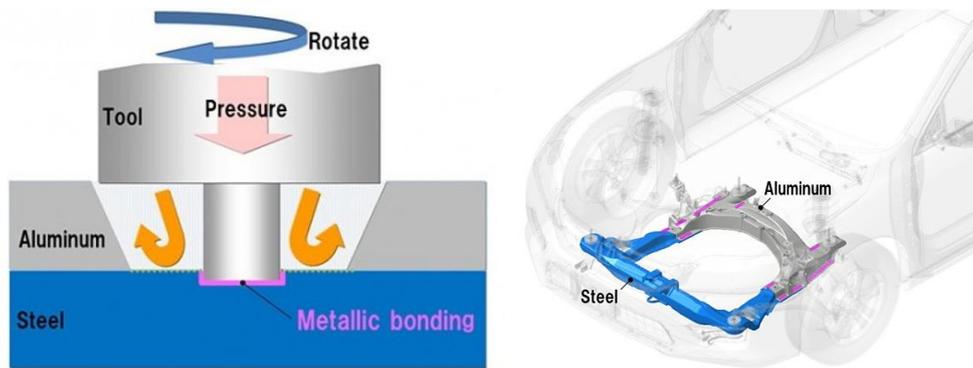


Friction stir spot welding of steel to aluminium (MX-5 trunk lid and bolt retainer)

(Source: Mazda)

Galvanized steel helps to prevent galvanic corrosion that results from the contact of two types of metal. The joining tool pushes aside the zinc coating. Then the heat bonds the two metals together. A residual layer of zinc remains on the metal surrounding the area where the two metals are joined, preventing local corrosion of the metals.

A variant of the linear friction stir welding process (see 7.1.2) can be also used to form continuous structural aluminium/steel joints. A stable metallic bonding between steel and aluminium is achieved by moving a rotating tool on the top of the aluminium which is lapped over the steel with high pressure. The technology is used in practice to manufacture aluminium/steel subframes.

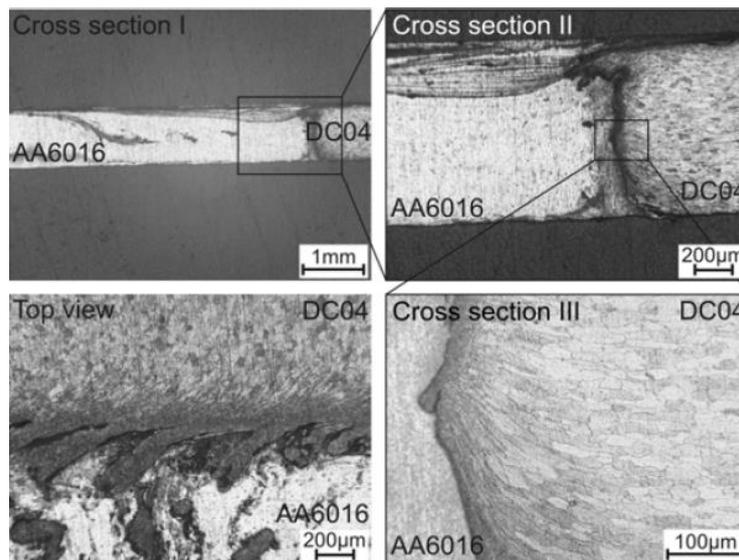


Friction stir welding of aluminium to steel

(Source: Honda)

11.2.3.3 Laser assisted friction stir welding

In an effort to produce hybrid tailor welded aluminium-steel blanks by friction stir welding, the steel blank was preheated with a laser beam in order to diminish the flow strength of the material. The diode laser spot was positioned directly in front of the welding direction of the tool. The results show the high potential of laser assisted friction stir welded steel/aluminium tailored hybrid blanks in a sheet thickness of about 1 mm. Simultaneously, the welding speed could be significantly increased up to 2000 mm/min.



Appearance of the weld seam in a cross section (I-III) and a top view

(Source: M. Merklein et al., University of Erlangen)

11.2.4 Brazing and soldering

Brazing (see 6.1) and soldering (see 6.4) have a significant advantage over other molten metal joining techniques. The formation of brittle intermetallic compounds can be significantly inhibited through the use of brazing alloys and solders with low melting points. Dissimilar metals and even non-metals (i.e. metallized ceramics) can thus be joined to aluminium. For joining ceramics to metals, thin metal layers are usually deposited onto the ceramic part prior to brazing in order to facilitate the bonding process.

11.2.4.1 Brazing

Furnace brazing, however, encounters some difficulties to ensure the required short process cycles (fast heating/cooling). Specific problems associated with torch brazing include the need for high levels of technical skill. Arc and, in particular, laser brazing offer the prospect of solving these problems.

Aluminium can be brazed readily to other metals such as nickel, titanium and – with some limitations – steel. Only a thin layer of intermetallic phases is formed. However, when brazing aluminium to magnesium and copper, i.e. metals where the phase diagram shows a low melting eutectic, much larger particles of brittle intermetallic phases develop. Thus, brazing aluminium to Mg or Cu is practically not possible.

Brazing processes require the use of a filler alloy and an adequate fluxing agents. As an example, suitable options when brazing aluminium to stainless steel are:

- NOCOLOK® flux and Al-Si filler alloys or
- CsAlF complex flux (melting range between 420 and 480 °C) and a 85 % Zn – 15 % Al filler alloy.

Joining of aluminium to stainless steel using the NOCOLOK® flux is carried out for different applications on large a scale for non-structural joints outside of the automotive industry. It works both with NOCOLOK® flux + Al-Si brazing alloy and with NOCOLOK® Sil flux. After the flux melts and the oxides are removed, a thin layer of intermetallic phases is formed which serves as a metallurgical bond between steel and aluminium. The thickness of the brittle intermetallic layer is a function of the brazing time and temperature; consequently the need for a short brazing cycle with fast heat-up and very short holding time at maximum temperature.

11.2.4.2 Soldering

Soldering is highly suited to join a wide variety of materials, including aluminium to other metals as well as ceramic materials. Conventional soldering uses lead and tin based solders or silver, copper, nickel or other precious metals and/or alloys that melt at a lower temperature than either of the materials being joined. The soldering alloy fuses into the surfaces of the materials being joined, forming a metallurgical bond without significantly melting either of the two materials. When soldering in air, fluxes are used to react with oxide surface layers and to shield the joint area.

When soldering dissimilar materials, the following aspects have to be considered when selecting the appropriate soldering system:

- The compositional compatibility of the solder with both interfaces.
- The differences in the coefficient of thermal expansion between the two materials.
- The differences in melting points.

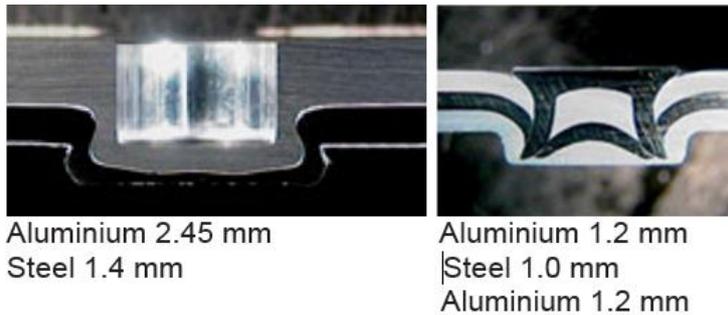
Since aluminium has a high coefficient of thermal expansion, soldering – which is carried out at significantly lower temperatures than brazing – may be the preferred solution in many applications.

An advanced soldering technology for dissimilar materials was developed by EWI. The EWI SonicSolder™ works in conjunction with the ultrasonic soldering process. Ultrasonic soldering offers the advantages of flux-less, lead-free soldering with the ability to join difficult-to-wet materials. The binary Sn-Al lead-free solder alloy allows for successful joining of aluminium, copper, titanium, glass, ceramics, and other difficult-to-bond materials.

11.2.5 Mechanical joining processes

Until recently, mechanical joining was the main technology used to join aluminium and steel components. In general, all the different mechanical joining methods used within the automotive industry (see section 8) are also suitable to join dissimilar metals. However, depending on the material combination (strength and ductility of both partners), some limitations may exist in particular for mechanical joining techniques which are based on forming and cutting processes (e.g. clinching, self-piercing riveting, flow drilling screws, etc.).

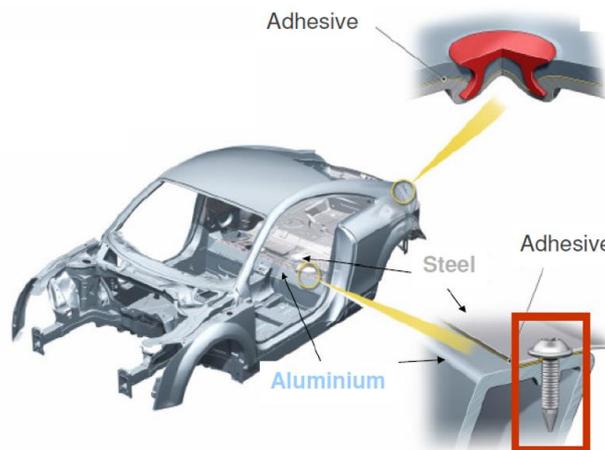
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Clinching (left) and self-piercing riveting (right) of aluminium to steel

(Source: Böllhoff)

Furthermore, thermal expansion effects must be considered both during design and in the assembly process. Subsequent thermal influences (e.g. during bake hardening of the lacquered body-in-white) may result in severe distortions of an aluminium body panel mechanically joined to a stiff steel structure. Proper measures have to be taken for compensating the differences in the thermal expansion coefficient.



Aluminium to steel joining technologies in the Audi TT

(Source: Audi)

In most cases, mechanical joining techniques are combined with adhesive bonding to increase the static and fatigue strength of joints and prevent any deterioration of corrosion resistance of joints caused by the contact between the dissimilar metals.

11.2.6 Adhesive bonding

Adhesive bonding (see section 9) is a standard joining technology for dissimilar materials. As mentioned above, adhesive bonding is also often used to mitigate galvanic corrosion when joining dissimilar metals. The adhesive must be compatible with both metals, and both metals may require some form of surface treatment, in special cases even including the application of an appropriate electro-coat primer. In addition, when bonding aluminium to another metal, for example, steel or magnesium, the difference between their respective thermal expansion coefficients is a major concern.

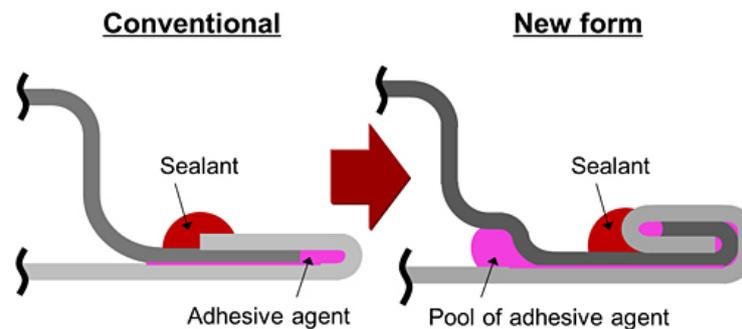
Adhesive bonding is key technology to join steel to aluminium in the automotive industry. But as a consequence of the different thermal expansion coefficients, rigid bonds that have worked in homogeneous designs, may now require some flexibility. Elastic bonding techniques provide the required amount of flexibility of an adhesively bonded joint without cohesive or adhesive failure. The characteristics of elastic adhesives enable successful bonding of materials with dissimilar coefficients of thermal expansion and maintaining bond strength and integrity in service. In addition, these types of adhesives help to minimize read-through of the bond, i.e. they prevent a visually noticeable appearance of the bond line on the surface.

Elastic bonding is not a new concept to vehicle design. Different types of adhesives are available for elastic bonding, e.g. polyurethanes and silane modified polymer formulations with a proven track record in truck and bus applications.

11.2.6.1 Hem flange bonding

Hem flange bonding is the standard solution when aluminium and steel closure panels are joined. In order to prevent any problems related to galvanic corrosion and thermal deformation between an aluminium outer panel and a steel inner panel, Honda recently presented three newly developed technologies:

- Adoption of "3D Lock Seam" structure, where the steel panel and aluminium panel are layered and hemmed together twice.
- Adoption of a highly corrosion-resistant steel for the inner panel and a new flange form that assures the complete filling of the gap with adhesive agent to prevent galvanic corrosion.
- Adoption of an adhesive agent with a low elastic modulus and optimised seam position to control thermal deformation.

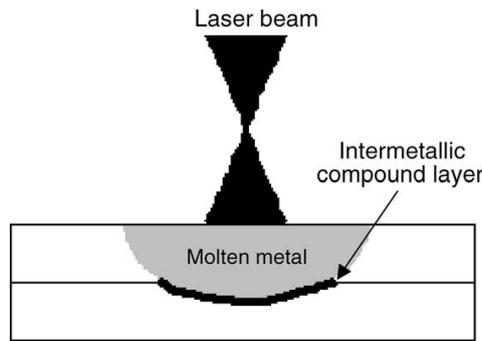


Optimised hem flange bonding technique to join an aluminium outer and a steel inner panel

(Source: Honda)

11.2.7 Joining aluminium to magnesium

The combination of aluminium and magnesium components offers interesting new lightweight solutions. Whereas in case of dissimilar joints such as steel/aluminium alloys, it is possible to realize a solid/liquid state reaction at the joining interface between the two metals where only the metal with lower melting temperature melts, it is difficult to apply this method to magnesium/aluminium alloys joint due to the small difference between their melting points. Numerous attempts have been made to join magnesium to aluminium using arc and resistance spot welding, but they have invariably led to failure. The two metals react to form brittle intermetallic compounds in the melted zone and the weld literally falls apart. However, laboratory laser welding proved the possibility of a controlled molten metal penetration depth in the lap joint configuration.

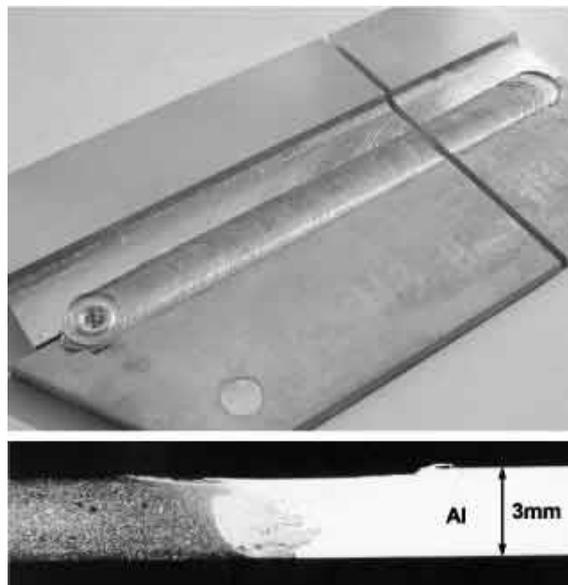


Laser welding of lap joint

(Source: R. Borrisutthekul et al., Science & Technology of Advanced Materials 6 (2005) 199)

It was found that an edge-line welding lap joint could be realized with the required shallow penetration depth of molten metal into lower plate, effectively reducing the reaction between the two metals and, thus, the formation of larger intermetallic compounds.

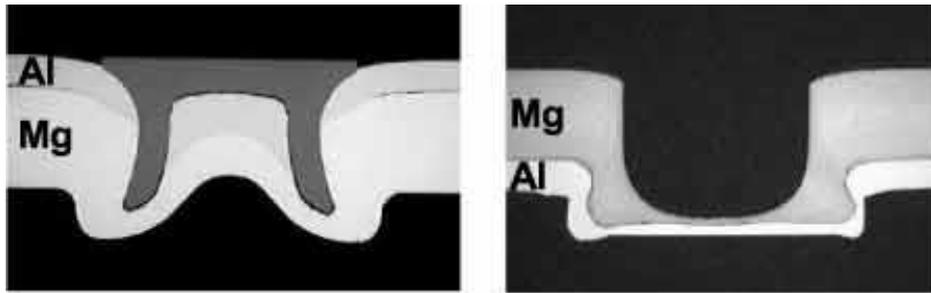
Some work has also been done to demonstrate the basic feasibility of the friction stir welding process to join magnesium and aluminium alloys. Initial results were encouraging. The two materials are plasticised, but do not melt. The joint is a complex mechanical interlock and there is no evidence for the formation of intermetallic compounds.



FSW of magnesium alloy (AZ91) to aluminium alloy (EN AW-2219)

(Source: TWI)

The most important methods for joining magnesium to other materials are mechanical fastening systems, often combined with adhesive bonding (in general with pre-fabricated holes in the magnesium part). However, in recent years, the self-piercing riveting and clinching techniques were also used with considerable success. The principal difficulty is the poor ambient temperature ductility of magnesium, which requires heating of at least the magnesium component prior to making the joint. Successful industrialisation of this process requires the development of machine tools capable of providing the right temperature conditions in an acceptably short time.



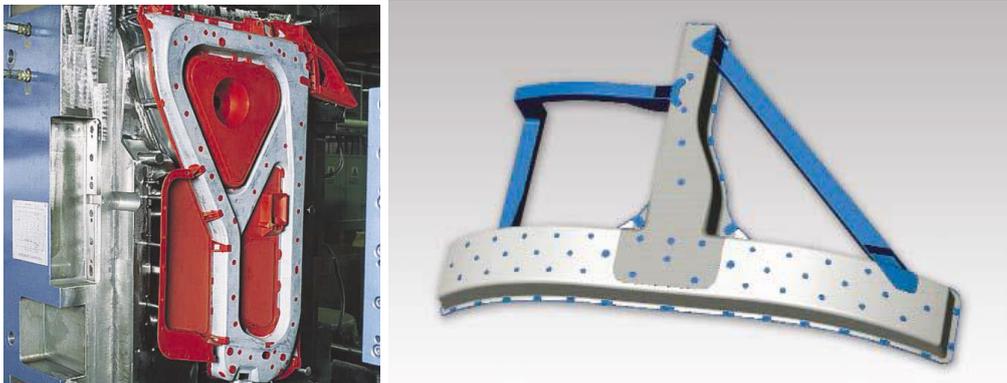
Self-piercing riveting (left) and clinching (right) of aluminium (1mm thick) and magnesium (3mm thick) alloys

(Source: TWI)

11.3 Joining aluminium to plastics and composites

The following consideration focus on processes suitable to join aluminium and fibre reinforced composites. Aluminium-plastic joints are usually not structural joints. In practice, adhesive bonding and specifically developed mechanical joining methods are mostly used.

Another most interesting possibility – which will not be covered here – is to join properly shaped aluminium components directly in the injection moulding process.



The injection moulding process combines metal stamping with plastic structures

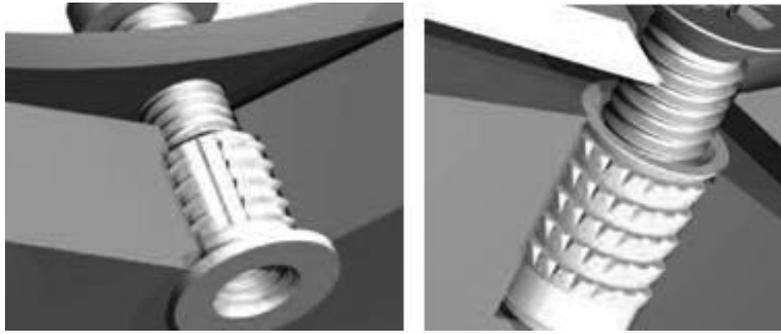
(Source: Lanxess)

11.3.1 Joining aluminium to plastics

Adhesive bonding is probably the least expensive joining methods for permanent bonds. Adhesive bonding uses commercially available materials that are specifically formulated to bond plastic parts to the other material.

11.3.1.1 Joining with mechanical fasteners

Specifically for assemblies that must be taken apart a limited number of times, mechanical fasteners (i.e. screws, bolts and rivets) are the least expensive, most reliable and commonly used joining methods. If the part is going to be disassembled regularly, metal inserts in the plastics should be considered. Rivets offer a simple, easily automated installation process that can be used in particular for plastic-to-sheet metal joints.

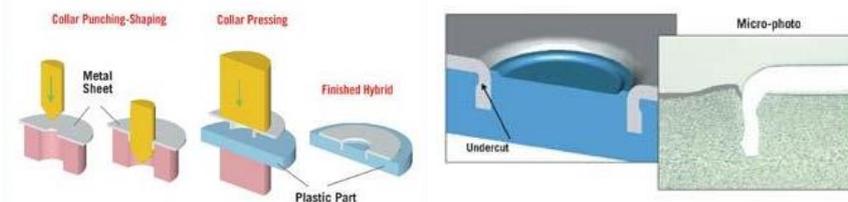


Inserts for thermoplastic parts: screwed-in (left) or joined by ultrasonic welding (right)

(Source: Tappex Ltd.)

In a typical large plastic and metal assembly where movement is restricted, high compressive or tensile stresses can develop since the expansion coefficient of plastics is four to six times higher. To avoid such problems, slotted screw holes in the plastic part should be used for temperature-sensitive designs.

Designed into the geometry of mating parts, snap fits offer a very inexpensive, quick and efficient joining method. Press fits must be designed with great care to avoid excessive stress in the assembly. A special mechanical method has been developed to create hybrid automotive front-end assemblies. The approach is to form projecting annular collars in a metal sheet and then to cold-press those collars into plastic parts. Undercuts in the metal collars act as claws to firmly lock together the sheet metal and moulded plastic. The collar-joining approach well with a number of reinforced and unreinforced materials, including nylons, PBT, and polypropylene, although most work to date has been with 30 % glass-filled nylon 6 and 66. No significant crazing or fracturing occurs when the metal collars are pressed into the plastic.



Collars punched out of sheet metal are cold-pressed into plastic parts

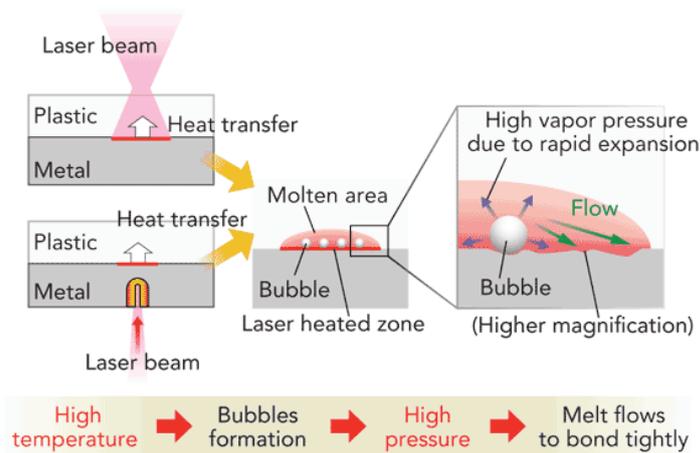
(Source: BASF)

Also clinching seems to be a promising technology to join metals with short fiber reinforced polymers since there is no thermal influence on the materials and the process requirements to surface finishing are low. One of the main challenges in designing a suitable clinching process is to consider the quite different stiffness, plastic behavior and forming limits of these two materials.

11.3.1.2 Laser-assisted metal and plastic joining

Laser-assisted metal and plastic joining is applicable to many combinations of metals (e.g. steels, titanium, and aluminium alloys) and plastics (e.g. PET, polyamide (PA), and polycarbonate (PC)). The laser beam heats the metal either from the plastic or the metal side of a lap joint and melts the plastic near the joint interface. The key point is the formation of small bubbles (diameter 0.5 mm or less) which induce a high pressure in the molten plastic. Thus the molten plastic is forced to the metal surface. Anchoring effects in concavities of the surface topography, physical Van der Waals forces and chemical bonding through the oxide film produce a strong joint.

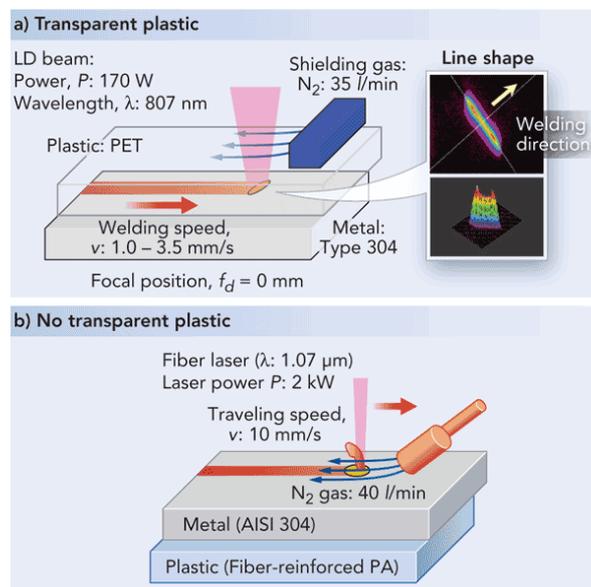
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Mechanism of laser-assisted metal and plastic joining (Source: S. Katayama, Osaka University)

The surfaces of plastic sheets and metal plates are cleaned with alcohol; no other surface treatment is required. If the plastic sheet has more than 60% transparency, it may be placed at the upper side. The transmitted laser beam is absorbed to heat the metal surface, and the plastic near the joint can be melted to form bubbles by the heat conducted from the metal. A shielding gas should be used to keep the top plastic sheet surface clean and cool.

For non-transparent plastics (e.g. GFRP and CFRP with high laser absorption), the metal sheet is placed on top. If the metal is thick, a partially penetrating weld should be produced to heat the plastic near the joint interface. The metal interface near the lap joint is not melted, but the plastic on the metal plate is melted and the required small bubbles are formed.



Laser-assisted metal and plastic joining (Source: S. Katayama, Osaka University)

11.3.2 Joining aluminium to composites

Composite materials consist of a polymeric matrix resin which is used to bind fibrous reinforcements into the combined material. The type, volume fraction, length and layout of the fibres determine its mechanical properties. Composites can have complex directional mechanical properties, differing by in-plane and out-of-plane orientations. In the fibre direction, properties such as tensile strength, modulus, and yield strength are considerably

higher and depend on the adhesion between the resin matrix and the fibre. Perpendicular to the fibre, the properties approach those for the matrix resin alone.

Composites can be divided into two major classes based on the matrix resin: thermoset composites and thermoplastic composites. A thermoset polymer matrix composite cures and crosslinks when heated; it cannot be re-formed by heating. Examples are epoxy, acrylic, or urethane reinforced with either glass or carbon fibres. A thermoplastic matrix composite softens with heating and continues to soften every time it is heated. Examples are polypropylene or nylon, also reinforced with glass or carbon fibres. These can be molded into shapes or welded by using some form of heat and pressure.

Both thermoset and thermoplastic composites may be laminated, impregnated fabric structures. A typical laminar carbon-fabric composite might contain 50 – 60 vol. % reinforcement. Thermoplastic composites, especially, may take the form of short- or long-fibre random reinforcement mixed into the bulk and then molded into shapes. These may contain as much as 50 vol. % reinforcement, which gives rise to quasi-isotropic behavior, except at the surface, which will be high in resin.

Joints between aluminium and either a thermoset or thermoplastic composite are generally achieved by adhesive bonding or a combination of adhesive bonding and mechanical fasteners. However, joining a composite panel to aluminium presents some problems. The mechanical anisotropy of the composite in the joint region must be accounted for in the design. In a shear-loaded joint, the fibers nearest the faying surface should be oriented along the joint in the direction of the maximum expected shear. Therefore, the fibre direction might be parallel to the long axis or the short axis of the joint, depending on the expected loading. Often, the layer nearest the joint is oriented to give maximum strength performance in the direction of maximum stress. To deal with complex loading at the faying surfaces, biased fibre layers can be oriented nearest to give an average directional stress distribution.

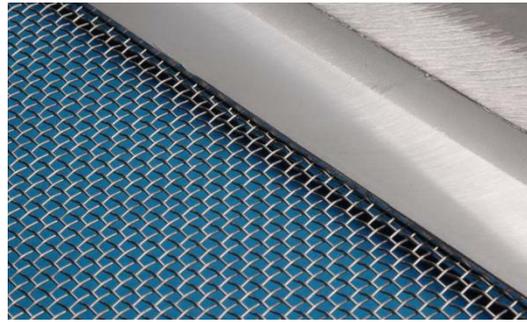
It is also necessary to allow for thermal mismatch. The coefficient of thermal expansion for epoxy-based parts matches that of aluminium fairly well. In comparison, the coefficient of thermal expansion for a thermoplastic composite, such as glass fibre-polypropylene, is higher, and so has the potential for thermal strains at the bond line.

Furthermore, when carbon fibre composites are in contact with aluminium, galvanic corrosion is a concern. An adhesive can provide a galvanic corrosion barrier. An electro-coat layer could provide additional protection. However, any through-holes (e.g. for riveting) require specific attention.

11.3.2.1 Transition joints

Transition joints are important auxiliary means to join metals and composite materials. They are normally metallic elements which are integrated into the composite during part manufacturing. Attachment to the metal part is then possible using conventional joining methods.

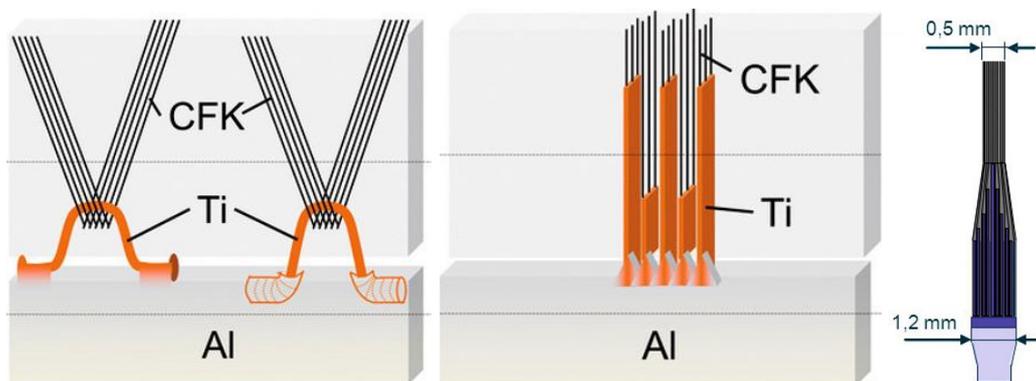
Different concepts are evaluated to realize transition structures between aluminium and carbon fibre reinforced composites. As an example, using the Stir-lock™ technique (see 11.2.1.1), reinforced transition joints can be produced. A stainless steel mesh, which provides a skeleton for the application of the composite material, is joined to an aluminium element by friction welding.



**Stainless steel mesh reinforcement joined to aluminium by the Stir-lock™ technique
(Source: TWI)**

Another possibility is a “wire” concept characterised by a parallel arrangement of miniaturised loop connections. It consists of a carbon fibre-titanium wire-textile which is joined to an aluminium sheet. A carbon fibre loop is threaded through a titanium wire loop on one side. On the side opposite, the titanium wire loops are joined to the aluminium component.

The “foil” concept can be characterised as a hybrid laminate. It consists of carbon fibre reinforced plastic layers which alternate with titanium foils. The area of the laminate which only consists of titanium foils is then welded to aluminium.



**Titanium wire (left) and foil concept (right) to join CFRP-aluminium structure
(Source: Fraunhofer IFAM)**

Both joint configurations, are in principle suitable to produce load-bearing carbon fibre reinforced plastic-aluminium structures, when using a laser beam welding process to join aluminium to titanium.

11.3.2.2 Adhesive bonding

Thermoset composites are easier to adhesively bond than thermoplastic composites because they have higher surface wettability. Epoxy, urethane, or acrylic adhesives can all be used for adhesive bonding with aluminium. Epoxies are especially reliable when used with epoxy-based composites because they have similar flow characteristics.

Careful preparation of both material surfaces is essential to achieve a high quality adhesive bond. The required surface treatment for the composite component varies depending on the type of composite and the adhesive used. The recommended preparation of many composite materials includes a solvent wipe (to remove loose surface dirt and oil) and an abrading operation. Abrasion should be done carefully to avoid damaging composite surface fibers. In some cases, a primer must be used to coat the composite before applying the adhesive.

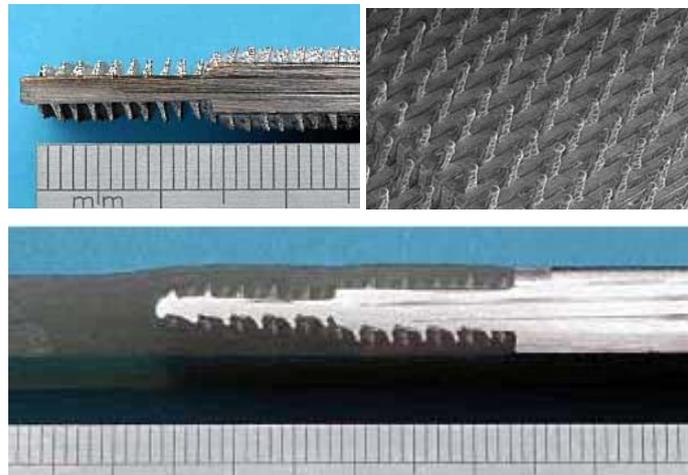
Thermoplastic composites do not wet well with adhesive and usually require a form of surface activation. This can be a flame, corona, or a plasma treatment that oxidizes the surface to increase wetting. A primer can also improve wetting. Once the polymer surface is acceptable for bonding, the system can be adhesively bonded or rivet-bonded. Efforts have been made

to weld-bond thermoplastics to metals. So far, these are mostly heat seal joints and may involve adhesives as well. But this is clearly an area which must be watch in future.

Another possibility to adhesively bond composites to aluminium is the use of a primed aluminium component (preferably an electro-coat primer). The bond would then be between the primer and the composite. Normally the joint can then be designed with the assumption that the weak link is the primer/aluminium interface.

A successfully bonded joint with a composite member will be one in which the composite fails rather than the adhesive joint. Typically, a laminated composite structure will fail between the first and second plies under the phenomenon of interlaminar shear failure. In this situation, the layers of fabric are held together only with resin (unless the material is braided), and the fault begins in the resin between two layers and propagates along the fabric interface.

Joints with enhanced mechanical performance can be produced by the combination of adhesive bonding and mechanical interlocking between composite materials and metals. There are different possibilities to produce a metal surface topography which is optimized for mechanical interlocking. As an example, the Surfi-Sculpt surface topography is the basis for the proprietary Comeld™ method developed by TWI.



Surfi-Sculpt™ surface treatment (top) and double step Comeld™ joint (bottom)
(Source: TWI)

Comeld™ joints can be produced from a wide variety of metals and composite materials using a variety of processing techniques. In the joints shown above, the matrix of the composite was used as the adhesive; however, an additional adhesive layer may be used at the interface between the composite material and metal.

11.3.2.3 Mechanical fasteners

Mechanical fasteners are often used to join aluminium with plastics and composites, in many cases combined with adhesives.

Different standard mechanical joining methods (e.g. rivets, two-piece bolts or blind fasteners made of stainless steel or aluminium) use pre-drilled holes, both in the aluminium and the composite part. When specifying the applicable mechanical fasteners, several factors must be considered:

- Thermal expansion of the fastener in the joined materials (differential of the thermal expansion coefficients of the fastener with respect to aluminium and the composite).
- The effect of drilling on the structural integrity of the component as well as the possible fibre delamination caused by the fastener under load.
- The possibility of water (humidity) intrusion between the fastener and the aluminium/composite material.
- Possible galvanic corrosion effects at the aluminium/composite joint.

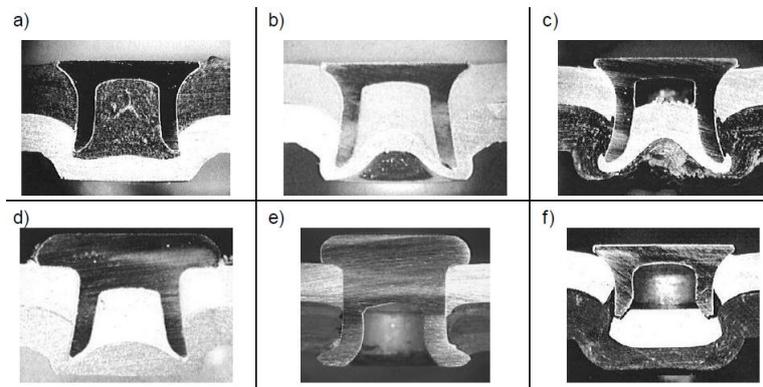
Fasteners for composites should have large heads to distribute the load over a larger surface area in order to reduce crushing of the composite material. Fasteners should fit as close as possible to reduce fretting effects in the clearance hole. Interference fits may cause

delamination of the composite and should be avoided. If an interference fit is necessary, special sleeved fasteners can limit the chances of damage in the clearance hole. Fasteners can also be bonded in place with adhesives to reduce fretting. Furthermore, in carbon-fibre reinforced composites, contraction and expansion of the fasteners can cause changes in clamping load.

Drilling and machining damage composite materials. The number and size of defects (e.g. delamination, resin erosion or fibre breakout) allowed in a structure depend on the application. For instance, delamination is a much more serious defect than fibre breakout in a carbon-fibre composite application. Applicable drilling techniques and tools are determined by the resin, the fibre (or fibre combination) in the resin as well as the way the fibres are configured.

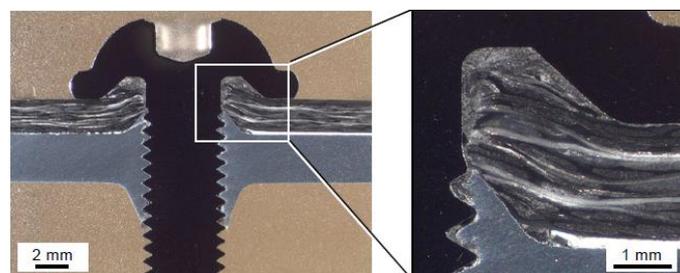
When carbon-fibre composites are cut, fibres are exposed and can absorb water and thus weaken the material. Local application of sealants can prevent moisture absorption, but this both complicates the process and prevents to maintain electrical continuity between the composite fibres and the fasteners. Moreover, carbon-fibre composites may corrode galvanically if aluminium fasteners are used. A solution is to apply a suitable coating to the fasteners. Another possibility is to replace the aluminium fasteners by titanium and stainless steel fasteners.

Similar problems as with pre-drilled holes in the composite material have to be considered for joining elements which form their own hole (e.g. flow drilling screws, self-clinching functional elements, self-piercing rivets, etc.). The cut through fibres reduce the load carrying capacity. Friction effects between the self-cutting joining elements and the fibre reinforced composite as well as the introduced axial forces lead to delamination and other damaging effects. In addition, the composite material is being crushed. The respective damaging mechanism – and the appropriate countermeasures – are still under investigation. Nevertheless these types of mechanical joining processes are of high interest for the design of future lightweight vehicles.



Self-piercing rivets used to join an aluminium alloy sheet (EN AW-6181A) to glass fibre reinforced composites (a,c,e,f) and to ABS plastic (b,d)

(Source: University of Paderborn)

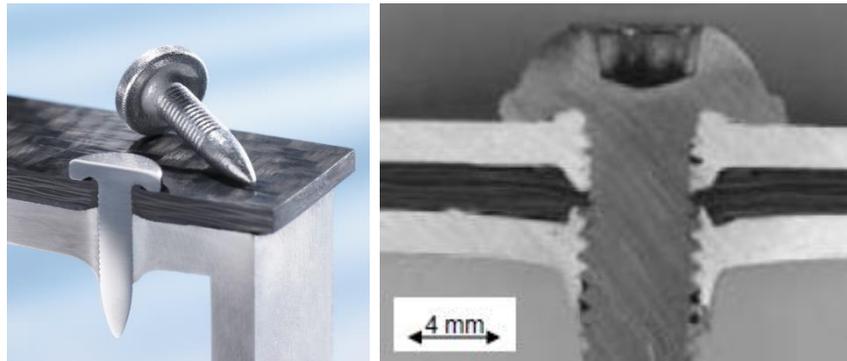


Hole and thread forming screw joining a fibre reinforced thermoplastic (2 mm) and a 3 mm aluminium alloy sheet (EN AW-6181A)

(Source: University of Paderborn)

Joining is generally easier when the ductile aluminium part is used as the bottom layer, i.e. if the joining elements first cuts through the carbon fibre composite. Therefore, an interesting

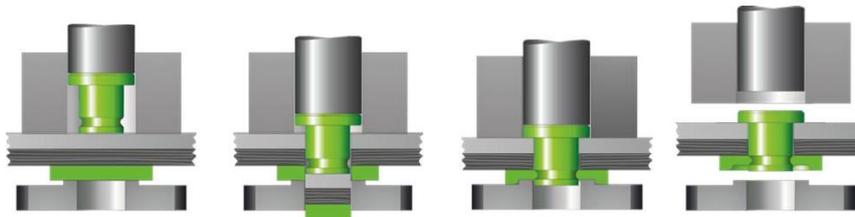
approach is also to use an aluminium counter piece for a joint where the aluminium sheet is positioned on top of the carbon reinforced composite.



Hybrid CFRP/aluminium profile joint adhesively bonded and fixed by RIVTAC® tack-setting (left) and a joint using a flow forming screw (right) with an aluminium counter piece

(Source: Böllhoff/Volkswagen)

A further development of the counter piece concept is a proposal made by the University of Paderborn. In this case, a solid self-piercing rivet is used with a suitable closing element on the composite side.



Joining principle using a solid self-piercing rivet with a closing element

(Source: University of Paderborn)

11.3.2.4 Friction spot welding

Friction spot joining (see 7.1.3) is a possible technique to produce hybrid structures by joining aluminium alloys with high performance thermoplastic composites. A non-consumable three-part tool is used to generate frictional heat. The tool comprises of a stationary clamping ring, as well as a pin and a sleeve which can rotate and move independently.

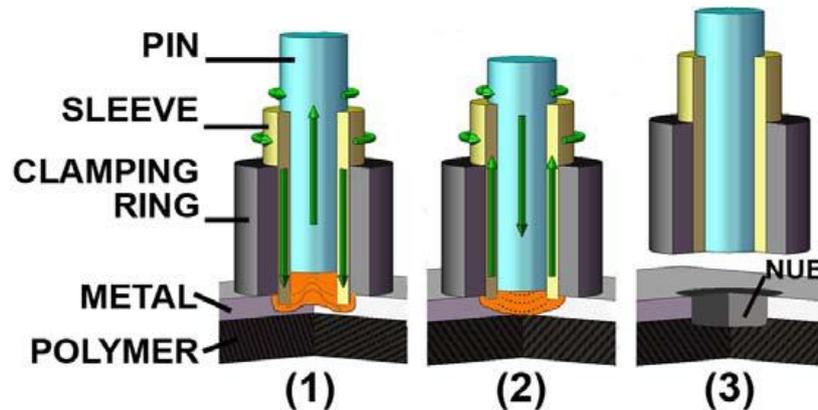


Friction spot joining tool

(Source: Helmholtz Research Center, Geesthacht)

The joining partners are clamped together in an overlap configuration with the metal piece on top of the polymer or composite against a backing plate. The sleeve and pin start to rotate in the same direction. Then, the sleeve plunges into the metallic sheet to a pre-defined depth while the pin retracts upwards. Due to the friction between the sleeve and the metal, the

temperature rises locally and the plasticized metal is squeezed into the reservoir left behind by the retraction of the pin. In the second step, the pin is forced against the soften metal to refill the key-hole. In this step, sleeve and pin return to their original position. Finally, the tool is retracted and the joint consolidates under pressure.

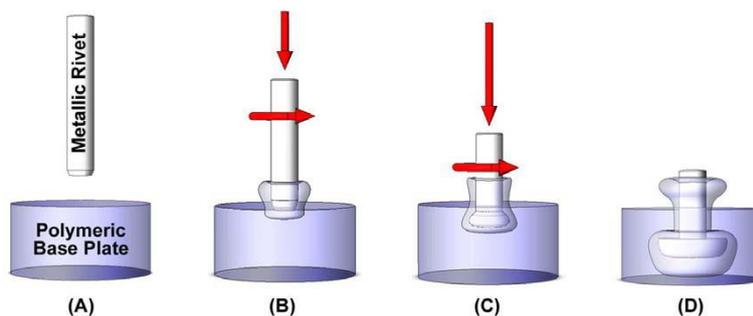


Friction spot joining technique for polymer-metal joining

(Source: Helmholtz Research Center, Geesthacht)

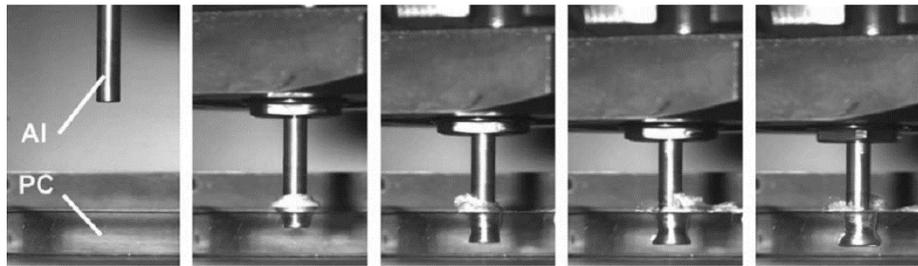
During the joining process, heat flows by conduction from the metallic part to the composite and melts a thin layer of the polymer matrix at the interface. The thermo-mechanical phenomena involved in the process result in two bonding mechanisms: Mechanical interlocking due to the metallic nub created at the metal-composite interface and adhesion bonding since the thin layer of the molten polymer produced in the spot region spreads throughout the entire lap area due to the low viscosity of the molten polymer.

Friction riveting (FricRiveting) is another innovative joining concept for polymer-metal hybrid structures, developed and patented by the Helmholtz Research Center Geesthacht in Germany. The basic configuration includes a rotating cylindrical metallic rivet which is inserted into a polymeric base plate. Heat is generated by the high rotational speed and the axial pressure. Due to the local increase of temperature, a molten polymeric layer is formed around the tip of the rotating rivet. As a result of the low thermal conductivity of the polymer, the further local temperature increase leads to the plasticizing of the metallic rivet tip. While the rotation is being decelerated, the axial pressure is increased and the plasticized rivet tip is deformed and anchored in the polymeric plate. After the consolidation under pressure, the joint is held by the anchoring forces related to the deformed tip of the rivet, as well as by adhesive forces in the polymer/metal interface.



Schematic view of the FricRiveting process

(Source: Helmholtz Research Center, Geesthacht)



FricRiveting of aluminum EN AW-2024 and polycarbonate

(Source: Helmholtz Research Center, Geesthacht)

The technology is adequate to produce overlap riveted joints between metal-polymer, metal-composite and composite-composite connections. Thermoplastic polymers or even fiber reinforced composites can be joined. The main process parameters are:

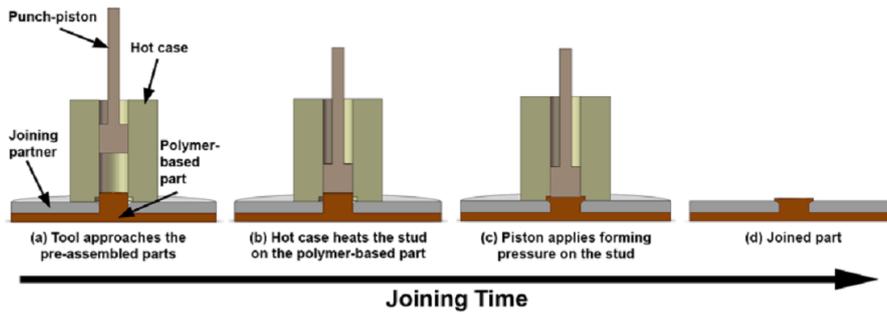
- Rotational Speed (angular velocity of the rotating rivet): It is important in the heat generation and associated phenomena.
- Joining Time: It controls the joining speed as well as the amount of heat energy supplied to the molten polymeric film, influencing the level of volumetric defects related to thermo-mechanical processing.
- Joining Pressure: The main role of this process parameter is to control the rivet forging and consolidation phases, but it is also related to the normal pressure distribution and heating of the rubbing surfaces.

11.3.2.5 Injection clinching joining

Injection clinching joining is a new joining process (patented by Helmholtz-Research Center, Geesthacht) for hybrid structures composed of a thermoplastic-based partner and a metallic or thermoset partner. The working principle is to produce joints through heating and deformation of a thermoplastic element, such as a cylindrical stud integrated in the polymeric partner, which is previously inserted in a drilled hole of the metallic / thermoset component, therefore creating a rivet from the structure itself.

Injection clinching joining joints make use of specially designed cavity profiles in the through-holes of the joining partner. The molten/softened polymer fills the cavity and remains anchored after the joint cools down and consolidates; the mechanical performance is improved by the additional anchoring performance. By the end of the process, a tight joint is obtained in which there are no additional parts other than the joining partners. Possible cavity profiles include chamfers and profiles such as threaded and dove-tail.

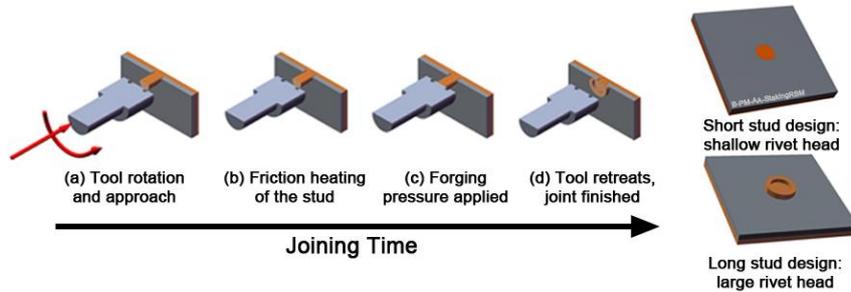
The electrical-heating injection clinching joining process is shown in the figure below. A polymer-based part with a protruding stud is pre-assembled with a joining partner containing a drilled hole so that the stud fits into the hole. The tool system consisting of a hot case and a punch-piston approaches the pre-assembled parts (step a). The stud is heated to the pre-determined processing temperature (step b), after which the punch-piston pushes the molten/softened polymer into the cavity (step c). The system is then cooled under pressure to reduce polymer thermal relaxation and the joint is consolidated (step d). The use of a hot case has the advantage of good heat distribution through the volume of the rivet, facilitating cavity filling. The main parameters of this process are the heating time and heating temperature. Joints can be produced in times from a few seconds to a few minutes.



Steps of the electrical heating injection clinching joining process

(Source: Helmholtz Research Center, Geesthacht)

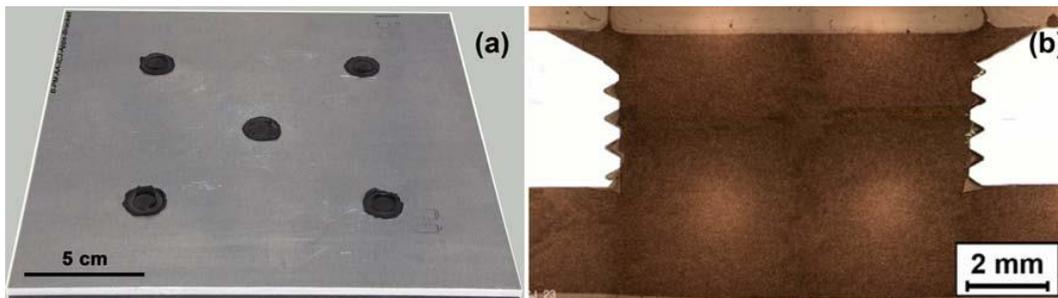
A variant is the friction-based injection clinching joining which uses a simple cylindrical tool. In its simplest configuration, a rotating tool approaches the polymeric stud (see figure below, step a), melting layers of the polymer through friction and pressure (step b). After the required amount of frictional heat is achieved, axial pressure is increased while tool rotation decelerate (step c); finally, the tool retracts and the joint is consolidated (step d). The design of the final rivet geometry can be tailored by defining the height of the original stud. A short stud will yield a shallow, more aesthetic rivet head, while a tall stud will deform into a large, more resistant rivet head. The main parameters of this process are rotational speed, joining pressure and joining time. This technique is fast (cycle times of a few seconds) and energy efficient.



Steps of the friction-based injection clinching joining process

(Source: Helmholtz Research Center, Geesthacht)

Injection clinching joining is a potential candidate to substitute metallic rivets on secondary structures, especially when joining plastic partners with dissimilar materials.



Injection clinching joining: Multiple spot hybrid structure (left) and cross-section of an EN AW-2024/PA66-GF joint (right)

(Source: Helmholtz Research Center, Geesthacht)