

# EAA Aluminium Automotive Manual – Joining

## 6. Brazing

### Content:

## 6. Brazing

### 6.0 Introduction

### 6.1 Brazing methods

#### 6.1.1 Dip brazing

#### 6.1.2 Flame brazing

#### 6.1.3 Furnace brazing

##### 6.1.3.1 Vacuum brazing

##### 6.1.3.2 Controlled atmosphere brazing

#### 6.1.4 Arc brazing

#### 6.1.5 Laser beam brazing

#### 6.1.6 Resistance brazing

#### 6.1.7 Induction brazing

### 6.2 General principles of the aluminium brazing process

#### 6.2.1 Aluminium alloys for brazing applications

#### 6.2.2 Brazing filler metals

#### 6.2.3 Joint design and assembly

#### 6.2.4 Cleaning before brazing

#### 6.2.5 Pre-assembly of the parts

#### 6.2.6 Brazing fluxes

#### 6.2.7 Flux application

#### 6.2.8 Brazing cycle

### 6.3 Soldering

#### 6.3.1 Soldering alloys

#### 6.3.2 Solderable aluminium alloys

#### 6.3.3 Soldering process

## 6.0 Introduction

Brazing is a metal-joining process where a filler metal is heated above its melting temperature but below the melting point of the metals being joined. The liquid filler metal is then drawn into the gap between the closely fitted surfaces of the joint by capillary action. Because of the importance of wetting and capillary effects, the quality of the surfaces to be joined is of utmost importance and the clearance between the parts must be small (generally less than 0.2 mm).

Soldering is a similar process to brazing, except that the process temperatures are lower. Traditionally, brazing and soldering of aluminium are distinguished from each other in the following manner:

- Soldering:  $T < 450\text{ °C}$
- Brazing:  $T > 450\text{ °C}$ .

Brazing produces excellent joints, in particular when joining thin-walled, compact parts. It is especially useful for the realisation of complicated parts with many joining spots per area unit, large area joints or inaccessible joints. The waterproof joints produced by the brazing process are specifically advantageous for the fabrication of products containing liquids like oils, water and/or coolants, even at relatively high operative pressures.

Since brazing does not melt the base metal, it allows for precise control of geometrical tolerances and low distortions. In addition, it provides clean joints with no need for additional finishing. Brazed joints are strong and, because the meniscus formed by the filler metal in the brazed joint is ideally shaped for reducing stress concentrations, they offer better fatigue strength than most welds. In addition, dissimilar metal joints like aluminium-steel, aluminium-titanium, aluminium-magnesium, etc., are also easily joined by brazing.

However, brazing of aluminium and its alloys requires careful temperature control since the brazing temperatures are generally close to the melting temperatures of the applicable parent alloys. Aluminium alloys typically melt in the range 560-660°C, while the standard aluminium brazing alloys (based on the Al-Si and Al-Si-Mg systems) melt in the range 520-610°C. The aluminium brazing temperature range is normally 580-620°C. As a consequence, high strength aluminium alloys of the Al-Cu and the Al-Zn-Mg-Cu systems (which generally have lower liquidus temperatures) are generally not joined by brazing.

Furthermore, it must be taken into account that – in many cases – the high brazing temperature significantly lowers the strength of the base aluminium alloy, i.e. potential softening effects must be considered when alloy and temper are selected. The exceptions are low alloyed, heat-treatable Al-Mg-Si alloys which can be quenched from the brazing temperature and then naturally or artificially aged to a higher yield strength level.

For proper brazing, the braze filler metal must be placed between the two components to be joined. The filler metal can be added as a wire, a metal powder mixed with flux or a thin sheet. Molten filler metal is then distributed between the closely fitting joint surfaces by capillary forces. Because the liquid filler metal can flow along the solid contact surfaces between two closely spaced components, brazing of blind joints is possible.

In most cases, however, a multi-layer sheet material is used to produce brazed aluminium assemblies. Aluminium brazing sheets are sophisticated multi-layer compounds consisting of a core alloy which provides the strength and other life cycle requirements and the filler metal, sometimes separated from the core alloy by a further alloy layer which acts as a diffusion barrier. In some cases, the brazing filler on one side is also combined with a clad layer providing additional corrosion protection on the other side. The filler alloy is clad on one or both sides of an aluminium core (usually produced by roll cladding or using a multi-layer cast rolling ingot (e.g. Novelis Fusion™ technology)).

During brazing, the liquid filler metal must be protected from the atmosphere by a suitable measure. A brazing flux, which cleans the brazing surfaces from any contamination and also removes the aluminium oxide surface layer when heated, is normally used for this purpose. In addition, the flux promotes base metal wetting and filler metal flow. Only if brazing is carried out within a furnace under vacuum, there is no need for flux addition.

Fluxes are chemical compounds applied to the joint surfaces before brazing. Traditionally, aluminium brazing has been based on chloride fluxes. More recently fluoride fluxes are commonly used. Fluxes can be added as powder or paste, alternatively the aluminium substrate or the filler material can be pre-coated with flux or a flux-containing composite filler rod can be used. In either case, the flux flows into the joint when heated and is subsequently displaced by the molten filler metal. Excess flux must be normally removed when the cycle is completed because many aluminium fluxes (particularly chlorides) can lead to corrosion. With non-corrosive fluxes, no post-braze cleaning step is required.

The most important automotive application of aluminium brazing is the fabrication of heat exchanger components. At the beginning of the 1970's, mechanically assembled aluminium heat exchangers started to replace the traditional copper and brass radiators. In the middle of this decade, the fluxless vacuum brazing process was introduced into large scale production. Finally the improved, flux-based controlled atmosphere brazing technique, developed in the early 1980s, enabled a breakthrough in the use of aluminium brazing material for heat exchangers. Today, controlled atmosphere brazing with non-corrosive fluxes (specifically the NOCOLOK® flux brazing technology) has evolved as the leading technology for manufacturing aluminium heat exchangers and aluminium has virtually replaced copper and brass.

A specific advantage is that the furnace brazing process can be easily automated. A major disadvantage of any brazing operation, however, is the difficulty of a non-destructive quality control of the resulting joints.



**Brazed aluminium radiator with plastic tanks**

(Source: Sapa)

### 6.1 Brazing methods

The most important brazing method for aluminium is furnace brazing (in particular for the production of heat exchangers). But the traditional aluminium brazing techniques like dip (flux) brazing and manual flame (torch) brazing still find their specific applications. In contrast to manual flame brazing, industrial brazing techniques such as dip and furnace brazing require fairly large capital investment and sophisticated production control systems.

In addition, also other heat input methods can be used. Industrially applied brazing methods include TIG (often referred to as GTA) and MIG (often referred to as GMA) brazing, plasma brazing, laser beam brazing or plasma brazing. These methods are selected in particular for small production volumes and when brazing aluminium to other metals. Furthermore, induction brazing or resistance brazing can be applied, specifically for brazing aluminium to steel.

### 6.1.1 Dip brazing

Dip brazing has been used widely and successfully for many years, in particular for complex assemblies. It enables rapid, uniform heating and can accommodate low dimensional tolerances. However, significant post-braze cleaning is required to remove flux residues and close attention must be paid to assembly design in order to avoid air traps.

Prior to the immersion into a molten flux bath, the assemblies are usually pre-heated to about 540°C. The flux is a molten mixture of chlorides of Na, K and Li with additions of fluorides of Na, Al and Mg and is periodically adjusted by further additions of molten chlorides and fluorides. The bath temperature should be controlled within  $\pm 3^{\circ}\text{C}$  and may not drop more than 6°C when the aluminium parts are immersed. Immersion time may vary from 30 seconds to 30 minutes depending on the size and weight of the assembly being brazed. It is very important that the flux residues are removed after brazing to inhibit corrosive attack of the parent material.

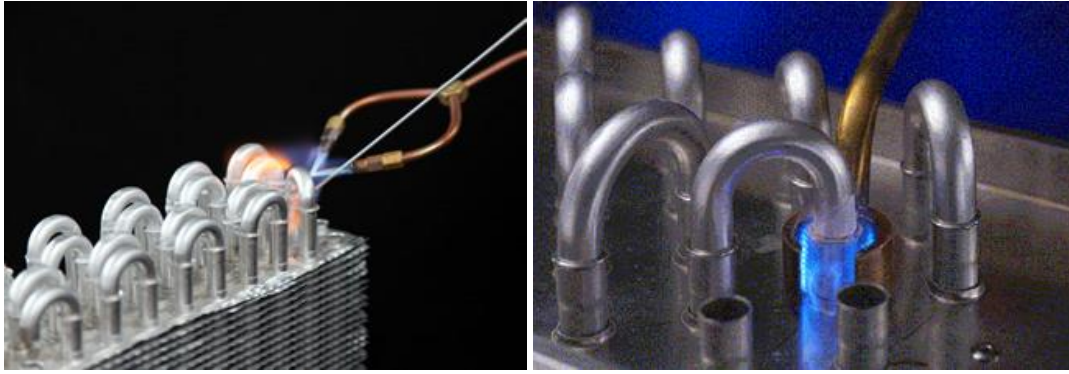
Another disadvantage of the dip brazing process is that it has a large impact on the environment. It produces corrosive vapours as well as large amounts of wastewater. Therefore, dip brazing is used decreasingly today.



**Dip brazing process**

### 6.1.2 Flame brazing

Flame (torch) brazing of aluminium involves locally applied heat typically generated by a slightly reducing oxy-acetylene, oxy-hydrogen or oxy-natural gas flame. The latter is usually the preferred gas mixture for aluminium torch brazing as it is cheaper and generally more controllable. Care must be taken to ensure even heat distribution. As with other aluminium brazing processes, close temperature control is important. While this is relatively straightforward in automated torch brazing, it is more difficult in manual brazing as there is no colour change in the aluminium to indicate temperature. As an aid to temperature indication, some torch brazing fluxes are formulated to change colour (as well as liquefy) when the appropriate temperature is reached.



**Flame brazing with a filler rod (left) and using clad material (right)**

Apart from the selection of flux and filler material, important process parameters are the cleanliness and proper geometrical alignment of the individual components. Filler metal may be pre-placed or added during brazing using a brazing rod. Post-braze cleaning to remove chloride flux residues is required.

Flame brazing uses relatively simple equipment, but is limited to the production of simple parts. Manual flame brazing is mainly used as a joining method for repairs. Provided proper filler metals and fluxes are selected, flame brazing can also be used for brazing aluminium to copper.

### 6.1.3 Furnace brazing

Furnace brazing is a semi-automated process which allows joining of fairly complex multi-joint assemblies. Furnace brazing is accomplished using a variety of techniques including different furnace designs (batch as well as continuous furnaces). Furnace brazing offers the flexibility to join a wide range of metals. The materials being joined determine the type of atmosphere in which the assembly is heated to join its components. In addition to air, vacuum, protective (inert) or reactive atmospheres are used.

Aluminium may be furnace brazed in air using flux. The brazing process follows the standard brazing procedure outlined above. The material surfaces are cleaned and fluxed, the filler metal is positioned and the assembled parts are placed in the furnace. A disadvantage compared to dip brazing is, however, the lower heat transfer rate. Slow and prolonged heating may result in liquation of the parent metal or in significant diffusion effects; insufficient heating may cause lack of brazing. Thus aluminium furnace brazing in air finds little practical application.

The most important furnace brazing methods for aluminium are brazing in vacuum and under controlled atmosphere. There is also considerably less impact on the environment compared to open furnace brazing and salt-bath brazing. The flux-less vacuum brazing process and the flux-based controlled atmosphere brazing (CAB) process solve the aluminium oxide layer penetration problem, a necessary precondition of any brazing process, by differing methods. Today, the CAB process is generally the preferred brazing process as it offers clear cost benefits (improved production yields, lower furnace maintenance requirements and greater process robustness). Newer developments also offer the possibility of flux-less CAB brazing.

#### 6.1.3.1 Vacuum brazing

In vacuum brazing, the parts to be joined are cleaned, brazing filler metal is applied to the surfaces, and the parts are then placed into the furnace. No addition of flux is required. After the furnace has been evacuated of air, the entire assembly is brought to brazing temperature. The vacuum eliminates any risk of oxidation or contamination which could occur when the braze filler metal melts and flows into the joints.





**Batch Vacuum Brazing Furnace**

**(Source: Ipsen)**

Vacuum brazing is a high-end joining technology because it results in parts with extremely strong joints and the absence of any residual corrosive flux. Typical vacuum aluminium brazing furnaces are either single chamber (batch type) or multiple-chamber (semi-continuous). Batch type furnaces are usually loaded horizontally, but can be also designed for vertical loading. Semi-continuous furnaces are horizontally loaded and typically automated using load carriers and external conveyor systems. In this case, a pre-chamber is usually added for thermal degreasing. Successful vacuum aluminium brazing requires a short process cycle (i.e. fast pumping and heating characteristics of the furnace) and good temperature uniformity at soak temperatures.

The mechanism of the flux-free brazing process under high vacuum is as follows:

- When an aluminium alloy is heated, the oxide layer cracks due to differential expansion before the brazing alloy starts to flow (the coefficient of expansion of aluminium is about three times greater than that of aluminium oxide).
- The liquid brazing alloy can pass through these cracks down to the bare base material, but only if oxidation of the aluminium in the cracks can be prevented. Consequently, the atmosphere must be completely devoid of oxygen.

Thus, there is not only a minimum requirement put on the level of the vacuum ( $10^{-4}$  mbar or better), but in addition, a getter material must be used to scavenge all oxygen atoms from the atmosphere. In the late 1960's, it was discovered that the presence of Mg vapour serves this purpose. Thus a key element of vacuum aluminium brazing is the use of magnesium as an additive to the filler metal and/or the base metal of the parts to be brazed:

- When the magnesium starts to vaporise at about 570 °C, it acts as a “getter” for oxygen and water vapour, thus improving the purity of the brazing vacuum and preventing further oxidation.
- The vaporising magnesium may detach partially the oxide layer. Magnesium will also reduce the aluminium oxide on the aluminium surface, enhance filler metal flow and promote uniform, accelerated wetting of the joint surfaces.

In vacuum brazing, the parts to be brazed are provided with sufficient quantities of magnesium, normally present in the filler metal or in the aluminium alloy components. When brought to temperature in the brazing furnace, magnesium diffuses to the surface and then vaporizes at 570°C due to low pressure of  $10^{-5}$  mbar. The magnesium vapour disrupts the oxide layer and thus enables the filler alloy to flow. But vacuum brazing can be even practiced using a Mg-free filler metal when magnesium powder is added separately to the brazing furnace.

The vaporization of the magnesium in a vacuum environment results in heavy outgassing during a short time period. Due to this gas load, the vacuum pumps must be adequately sized to maintain a good working vacuum.

In addition, precise temperature control and uniformity are important process parameters. The generally accepted temperature variation during a brazing cycle is +/- 3 to 5 °C. Thus it is

necessary to use a heat equalisation step at a temperature just below the solidus point of the braze filler metal to ensure that all parts of the component to be brazed reach the correct temperature at approximately the same time. When the further ramp-up to brazing temperature starts, the filler metal starts to melt, and the capillary wetting of the braze joints occurs. The length of time at brazing temperature must be kept to a minimum. After the brazing temperature soak is complete, it is followed by an immediate vacuum cooling cycle which solidifies the filler metal in the braze joints.

The precise temperature control and uniformity needed for vacuum aluminium brazing is achieved through the use of several separately controlled heating zones around the part. The surface temperature of the heating elements must be maintained as near to the part temperature as possible. A large temperature difference between the heating elements and the parts would result in an overheating of the part surface, possibly above the solidus temperature of the material.

Although capital costs of vacuum brazing equipment are relatively high and not all braze and parent alloys are suitable for vacuum brazing, vacuum brazing has been widely accepted by many volume producers. The process can be automated and, if properly controlled, allows the realisation of the cost and corrosion resistance advantages associated with flux-less brazing. A major disadvantage of vacuum furnace brazing is, however, the deposition of magnesium oxide inside the chamber and hot zone. Magnesium oxide deposits tend to retain water vapour which will slow down the vacuum pumping characteristics of the furnace and thus needs to be removed. Regular mechanical cleaning is the usual method for removing the magnesium oxide.

### 6.1.3.2 Controlled atmosphere brazing

In controlled atmosphere brazing (CAB), an inert gas is used to provide a non-oxidizing atmosphere in the furnace. The most commonly used inert gas is nitrogen, although nitrogen/hydrogen mixtures are also used in particular when aluminium is brazed to stainless steel.

There are various processes in use for the industrial scale manufacturing of heat exchangers. In the conventional CAB process, the ability to braze does not result from mechanical disruption of the oxide, but a non-corrosive, non-hygroscopic fluoride salt flux (typically potassium fluoroaluminate) is employed to dissolve and break up the oxide layer before the filler alloy melts. But there are also CAB brazing processes without using a brazing flux which are in particular used to braze surfaces inside a heat exchanger with are very difficult to flux.

The controlled atmosphere brazing technique has a number of advantages:

- Compared to open furnace brazing considerably less or no flux is used.
- The furnace muffle can be made from standard steel and has a much longer lifetime.
- Only small amounts of salt residues remain on the component.
- Neither washing nor other post-treatments are required after brazing as only non-corrosive flux types are employed in modern controlled atmosphere brazing of aluminium components.

#### a) Conventional CAB brazing

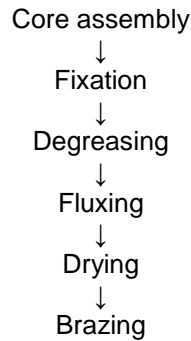
Since the early 1980's, controlled atmosphere brazing (CAB) with non-corrosive fluxes has evolved as the leading technology for manufacturing aluminium heat exchangers in the automotive industry. It offers cost benefits and shows less environmental impact compared to open furnace brazing and salt-bath brazing. The dominating NOCOLOK® technology uses a non-hygroscopic and non-corrosive potassium fluoroaluminate flux that does not react with aluminium neither in the molten nor in the solid state and the post braze flux residues have a very low water solubility.

The major problems that have arisen from the NOCOLOK® process have been flux costs and the necessity for the integration of fluxing systems, many of which will suffer from variable flux loading, flux handling and the damage that flux causes to the furnaces. The flux can also be difficult to apply, especially on internal joints and can cause problems in terms of furnace

## THE ALUMINIUM AUTOMOTIVE MANUAL

corrosion and cleanliness in the finished product. Moreover, it has been found that the flux can lose activity when exposed to magnesium. When the Mg content in the molten clad exceeds 0.3 %, the performance of the flux is reduced due to the formation of high melting K-Mg-F-compound. These compounds decrease the viscosity of the liquid filler and lead to poor brazing results. Thus, this process is not suitable for brazing magnesium-containing aluminum alloys.

The actual brazing process sequence depends on the specific component design, the cleaning method and the flux application technique. For automotive heat exchangers, the most common process sequence is:



This sequence minimizes handling of individual heat exchanger components, in particular handling of already fluxed components. Therefore, there is also minimum flux drop-off.

A fully configured controlled atmosphere brazing line includes an aqueous washer or thermal degreaser, a flux application unit, a dry off oven and the CAB furnace.



**Continuously operating CAB furnace with five preheat and seven braze zones  
(Source: Seco-Warwick)**

The loosely assembled and fixed heat exchangers are placed on an oven conveyor for processing.



**Aluminium radiators ready for brazing  
(Source: Seco-Warwick)**



## THE ALUMINIUM AUTOMOTIVE MANUAL

A thermal degreaser oven then removes the lubricating oils present on the heat exchangers from prior fabrication stages. It typically operates at 250 to 300 °C. The vapours from light evaporative oils are oxidized in the combustion chambers. If heavier lubricating oils are used, an incinerator at the oven exhaust may be required. The products must then be cooled down to ambient temperature prior to the fluxing operation.



**Thermal degreaser oven**

**(Source: Seco-Warwick)**

After degreasing, the component is sprayed with a flux suspension. Excess suspension is blown off and the component is then dried in a continuous oven. Alternatively, other flux application techniques can be used.



**Flux application station (left) and dry off oven (right)**

**(Source: Seco-Warwick)**

The actual brazing process is carried out after applying the flux in an inert gas furnace. The brazing furnace is isolated from external air in such a way that the components can continuously travel in and out without undesired air entry into the furnace. The water vapour concentration must be low (dew point – 40 °C or lower) and the oxygen concentration in the inert gas must be < 100 ppm. Ideally, a uniform surface temperature of the work piece of 600 +/- 5 °C is aimed for brazing. A suitable treatment for the furnace exhaust (i.e. dry scrubber) is required. After leaving the brazing furnace, the components are finished and can be removed from the conveyor belt. No further treatments are required.



**Controlled atmosphere brazing furnace**  
(Source: Seco-Warwick)

## b) Flux-less CAB brazing

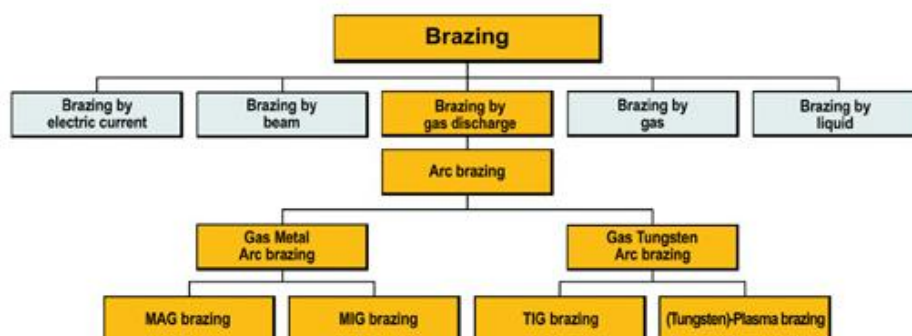
In order to avoid the problems related to the use of flux in the CAB process, various attempts have been made to develop a multi-layer brazing sheet which enables brazing in inert atmosphere without using a flux. Developments are still ongoing, thus only two possible approaches are outlined below.

A solution is a brazing sheet comprising of an aluminium core alloy clad on one or both sides with an Al-Si alloy brazing alloy containing 0.1-5% Mg and 0.01-0.5% Bi as an intermediate layer and a thin Al-Si alloy outer cover. During brazing, the brazing material in the intermediate layer melts as the temperature is increasing, but no oxidation occurs because the surface is covered with the thin covering material which remains solid. When the temperature is further elevated, some portions of the thin covering material close to the molten brazing material are locally molten since segregation effects locally reduce the melting temperature. The brazing material then seeps and spreads over the surface of the thin covering material due to volumetric expansion. New intensive oxidation does not proceed due to the inert gas atmosphere.

An alternative method is to coat the part to be brazed with a braze-promoting metal such as cobalt, iron, or, preferably, nickel. If properly applied, the nickel reacts exothermically with the underlying aluminum-silicon alloy, thereby presumably disrupting the aluminium oxide layer, and permitting the underlying metal to flow together and join the parts.

## 6.1.4 Arc brazing

Arc brazing can be classified into gas metal arc and gas tungsten arc brazing processes. The principle is largely identical to the respective welding processes using the braze alloy as the filler wire.

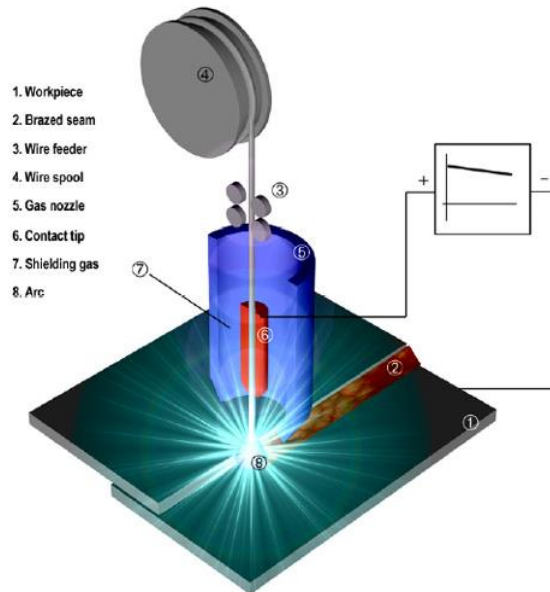


## THE ALUMINIUM AUTOMOTIVE MANUAL

MIG (also referred to as GMA) brazing was introduced in the 1990s. Very similar to MIG welding, the biggest difference is the use of a filler metal with a considerably lower melting point, since the base material must not melt during MIG brazing.

Since MIG brazing is done at low arc power, special precautions are required on the power source. Generally the pulsed arc process gives flatter seams than the short-arc process. Argon is often used as a shielding gas; also small amounts of other gases can be added to improve productivity and various properties.

The relatively low heat input makes MIG brazing particularly interesting for the welding of zinc-coated sheets in the automotive industry. Due to the low heat input, the zinc layer is left essentially undamaged and there is practically no thermal distortion. MIG brazing is also commonly used in automotive repair.



**Schematic presentation of MIG brazing**

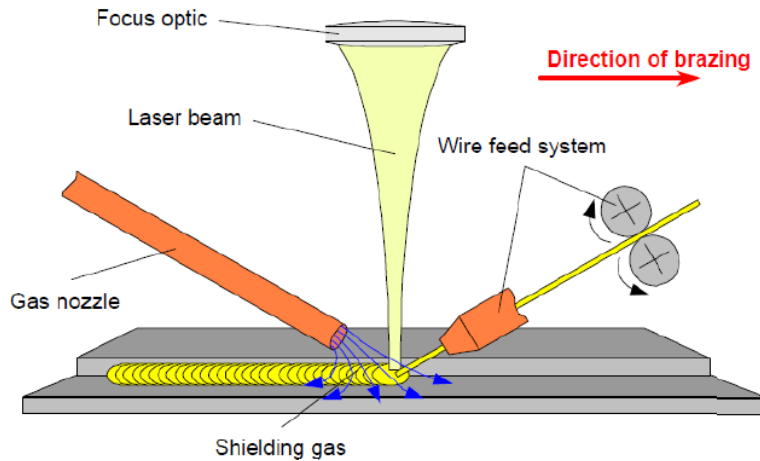
**(Source: MIG WELD GmbH)**

For aluminium materials, no industrial application of MIG brazing is known today. However, good results have been achieved in laboratory tests using newly developed filler wires at BIAS (Bremer Institut für angewandte Strahltechnik). Suitable filler materials should have a low melting temperature, good wetting characteristics on aluminium surfaces, adequate mechanical properties as well as a good corrosion resistance. Suitable filler wires (AlZn13Si10Cu4 and AlSi10Cu8Mg2Sn1) were produced by spray forming and subsequent forming processes (extrusion moulding and rotary swaging). These filler wire qualities were also successfully used for aluminium laser brazing.

With proper adaptations of equipment and processing procedures, also TIG (often referred to as GTA) and plasma methods can be used for brazing. In particular the plasma brazing process offers some advantages over MIG brazing (less spatter, better seam appearance, and minimum zinc evaporation). But again, these techniques – although in industrial application for steel – have not (yet) been applied for aluminium in practice.

### 6.1.5 Laser beam brazing

The principle of laser brazing is based on melting a cold brazing wire with a laser beam. The brazing wire is introduced into the braze seam via a wire feeder unit. The molten wire material then flows into the seam and forms a brazing joint. As an alternative to the use of a brazing wire, an aluminium sheet with a suitable surface cladding can be used. Multi-layer aluminium sheets such as Anticorodal®-200RW (Novelis Fusion™ alloy 8840) offer a cost-effective solution in this respect.



**Schematic presentation of laser brazing**

The laser brazing process is used in the automobile industry, for example, for joining galvanised vehicle components and body parts. It is a relatively cold joining process where the base material is not melted and any zinc layers next to the joint remain largely intact. Suitable joint designs are flanged-butt and fillets. The process provides very high travel speeds of up to several meters per minute at a very low heat input. The resulting distortion is rather low. In general, laser brazing joints have very smooth weld surfaces that normally do not require any further finishing, even in visible areas of the car body ("class A joints"). As an example, laser brazing is used for the ditch joint attaching the roof and the side panel of the car. Compared to laser welding or spot welding, laser brazing improves the aesthetics of the joint so that the ditch molding can be omitted.

The use of Nd:YAG lasers for this application has already been established. Recently, however, diode lasers are being increasingly employed. Typical process demands on the laser beam source for brazing are: laser power from 2 to 4 kW and spot size of from 1.5 to 3 mm at a working distance of about 150 to 250 mm. Both the solid-state and diode laser types equally fulfil these demands.

Laser brazing offers higher process speeds than arc brazing and can be easily automated by attaching brazing optics to a robot. For a further increase of the process speed, it can be extended to laser hotwire brazing by an additional current on the filler wire. The closely localised heat application reduces heat input and thus part distortion. An interesting option is also the possibility to improve the absorption characteristics of aluminium by a proper modification of the composition of applied flux. The flux composition can be successfully tailored according to the technical requirement dictated by the specific joining problem.

In practice, laser brazing is mainly used for joining aluminium to other materials, in particular steel. Laser brazing of aluminium to zinc-coated steel proved to be a cost-effective, reliable joining method (see 11.2.2.1).

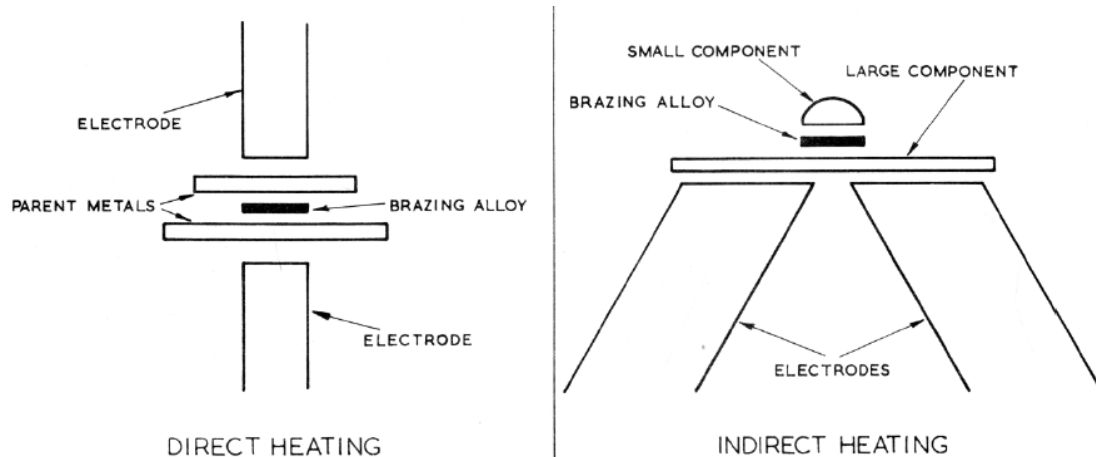
### 6.1.6 Resistance brazing

In resistance brazing, the joint to be brazed is made part of an electric circuit in which the local heat developed by the resistance to the passage of electric current melts the brazing filler metal and joins the elements. Resistance brazing is therefore suitable for applications where rapid and localized heating is required and where electrodes can apply the pressure required to establish electrical contact. The heat is generated in the workpieces, in the electrodes or in both, depending on the dimensions and on the resistivity of the respective materials.

There are two basic resistance heating techniques:

- For brazing high conductivity work pieces, the heat, generated in low conductivity (e.g. graphite) electrodes, will be transferred by thermal conduction to the joint through the base metal.
- For low conductivity base metals, high conductivity electrodes are used and the heat is developed electrode/work piece interface.

Two fundamental arrangements of electrodes and work piece are commonly used:



### Resistance brazing concepts

(Source: Johnson Matthey)

The direct heating approach can be used both with electrode heating and interface heating whereas indirect heating concept is only suitable for electrode heating.

Resistance brazing is ideal for joining small components, e.g. small temperature sensitive electronic or electro-mechanical metal components. In addition to working well with brazing alloys, this technique also works well with many lower temperature solder alloys. It can be performed in manual mode or in various degrees of automated modes, depending on configuration and production requirements.

### 6.1.7 Induction brazing

In induction brazing, two or more materials are joined together by a filler metal that has a lower melting point than the base materials using induction heating. Usually ferrous materials are heated rapidly in the electromagnetic field that is created by the alternating current from an induction coil.

With respect to aluminium, induction brazing is therefore only of interest when joining aluminium to other metals, in particular steels.

## 6.2 General principles of the aluminium brazing process

Because of its overriding industrial importance, in particular for the production of heat transfer equipment in cars, the following remarks concentrate on controlled atmosphere furnace brazing. However, information transfer to the other brazing processes (vacuum furnace brazing, dip and flame brazing, etc.) is easy and straightforward.



## 6.2.1 Aluminium alloys for brazing applications

### a) Suitable alloy compositions

Most non-heat treatable aluminium alloys and many heat treatable aluminium alloys can be brazed. Taking into account the normal aluminium brazing temperature range of 580 - 620 °C, as a general rule, the maximum percentages of alloying elements which may be present for an alloy to be brazed are: Cu - 1.0%, Mg - 2.0%, Mn - 3.0%, Si - 2.0%, Zn - 6.0%. The most frequently brazed non-heat treatable alloys are found in the 1xxx, 3xxx and low magnesium (< 2.5% Mg) 5xxx alloy groups. The heat-treatable alloys most frequently brazed are EN AW-6061, 6063, 6101, 6151, 6951, 7004 and 7005.

Alloys with a low melting point, i.e. alloys which would require brazing temperatures below those of existing filler alloys, are not suitable for brazing. This applies for example to the high strength aluminium alloys of the Al-Cu and the Al-Zn-Mg-Cu systems (e.g. EN AW-2011, 2014, 2017 2024 and 7075).

A second group of aluminium alloys to be avoided in flux brazing processes are 5xxx series alloys with a magnesium content > 2.5% since the base metal is only poorly wet and yet excessive penetration and diffusion is experienced due to the low melting point. Similar effects can occur in higher strength EN AW-6xxx alloys. During the braze cycle, magnesium diffuses to the surface and reacts with the surface oxide. The resulting oxides (MgO and MgO:Al<sub>2</sub>O<sub>3</sub> (spinel)) have a reduced solubility in the molten flux. Furthermore, Mg and/or MgO can react with the flux forming compounds, significantly reducing the flux effectiveness.

Aluminium casting alloys can be brazed too (if the solidus temperature of the alloy to be joined is sufficiently high), but brazing might be difficult when surface finish is poor or the metal is porous. Most critical are die castings because they do not wet easily with the filler metal. In addition, enclosed gases and other contaminants may cause blistering during brazing.

For controlled atmosphere brazing of heat exchangers, variants of the alloy EN AW-3003 are commonly used for the core. In special cases, also EN AW-1070 type materials are used. For vacuum brazing, EN AW-3005 is normally chosen due to its higher Mg content. In practice, however, aluminium brazing materials are specifically developed depending on the envisaged application and the applied brazing process. Thus there are numerous variants of core materials on the market.

The historically applied Al-Mn based alloys may be susceptible to inter-granular corrosion that is accelerated by the diffusion of silicon along grain boundaries from the cladding alloy during brazing. This encouraged the development of more corrosion resistant alloys ("Long Life Alloys"), i.e. modified EN AW-3xxx alloys showing a distinctive, elongated grain structure after brazing. In addition, during brazing, the silicon diffusion from the cladding leads to the precipitation of densely distributed AlMnSi particles at the interface between the cladding and the core alloy. The dense band of precipitates acts sacrificially to the core alloy, restricting corrosion to within this layer, and overcoming inter-granular attack. "Long life" brazing alloys are now widely used in many heat exchanger components.

If higher post-brazing strength levels are required, also heat treatable EN AW-6060, 6063 or 6951 alloys are applied as core material. During brazing, Mg<sub>2</sub>Si particles are dissolved and the elements are kept in a solid solution by rapid cooling. The material strength is then enhanced by the precipitation of small particles which are subsequently formed at room or slightly elevated temperature. But the use of AlMgSi alloys in controlled atmosphere brazing is rather limited due to their Mg content.

Even higher strength is offered by an adapted EN AW-7020 heat exchanger core material (AMAG TopClad® UHS 7020) where solution annealing also occurs at brazing temperature. However, in this case, a further barrier layer has to be introduced in order to prevent diffusion phenomena.

### b) Fabrication process

Aluminium brazing materials for serial production of brazed heat exchangers are sophisticated multi-layer compounds consisting of a core alloy which provides the strength and other life cycle requirements of the heat exchanger and the clad filler metal. Three- or five-layer compounds are commercially used; in the latter case, a diffusion barrier layer separates the core material from the filler. Furthermore, a protection layer can be clad on one side in order to prevent water-side corrosion. The applied core and cladding alloys depend on the chosen brazing process as well as the design and required performance of the heat exchanger.

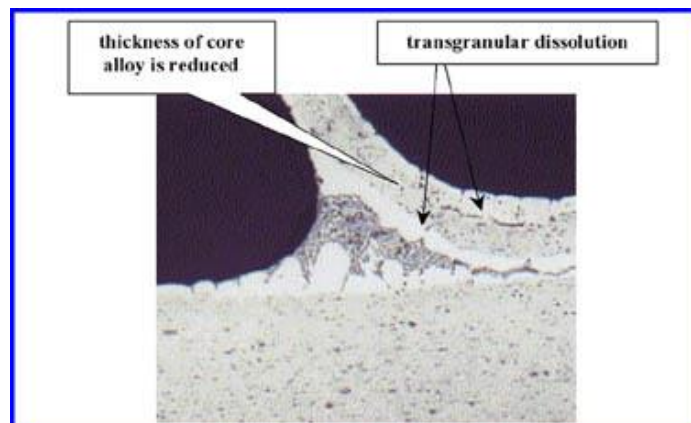
Today, two basic cladding techniques – roll bonding and cast cladding – are industrially applied. Roll cladding is a solid-state welding process, used to join similar and dissimilar aluminium alloys. The cladding layers are locally welded to the core slab; planar metallurgical bonding is achieved when the composite rolling slab is hot rolled. The cast cladding technique is based on the use of a modified direct chill mould which allows casting a unitary multi-layer rolling ingot from multiple molten metal streams (e.g. Novelis Fusion™ technology).

During brazing, only the clad brazing alloy melts while the core alloy remains solid. The design and the applied materials of the heat exchanger are adjusted to optimize the brazing result regarding the required post braze mechanical properties as well as the corrosion resistance. However, during the brazing cycle, elements of the core alloy and of the filler metal may diffuse from one to the other modifying the final properties of the assembly. As outlined above, such diffusion effects can enhance the corrosion resistance of the assembly by the formation of a sacrificial layer at the clad/core interface. However, there can be also adverse effects. Diffusion of silicon from the molten filler metal into the core alloy can take place, primarily along the grain boundaries. Consequently, the melting point of the affected area is lowered due the increasing silicon concentration and local melting of the core material can occur.

Dissolution of the core alloy must be minimised, because the reduction of the core thickness affects the strength and corrosion resistance of the product. It can even lead to a perforation of the core alloy. The extent of core dissolution is increased by:

- higher silicon levels in the clad,
- longer than recommended braze cycles,
- excessive peak brazing temperatures,
- excessive thickness of the clad alloy, and
- a design which allows pooling of the braze metal.

The most common factors leading to excessive core dissolution are linked to the processing conditions. Brazing beyond the recommended maximum peak temperature and/or extensive dwelling at brazing temperature are the primary causes.



**Local dissolution of the core alloy caused by silicon diffusion from the molten filler alloy**

### 6.2.2 Brazing filler metals

All of the commercially available filler metals suitable for aluminium brazing are based on the Al-Si eutectic system with the eutectic point at 12.6 wt% Si. Al-Si alloys are specifically used for brazing of aluminium components to minimise the risk of galvanic corrosion.

For all Al-Si brazing filler alloys, the solidus or the point at which melting begins is 577°C. However, for non-eutectic compositions, melting occurs over a temperature range. Between the solidus and liquidus temperature, the filler metal is partially molten, existing as both solid and liquid. Before the filler metal starts to flow, more than 60% of the material must melt, i.e. there is a minimum (threshold) temperature for each filler metal alloy in the brazing process.

Various brazing filler metals are used in industrial practice. Typical commercial filler metals contain from 6.8% to 13% Si:

- **EN AW-4343 (6.8 to 8.2% Si)**  
This alloy (melting range: 577 to 605°C) has the lowest Si content and consequently the longest freezing range. It is the least fluid of the filler alloys and the least aggressive at dissolving the core alloy.
- **EN AW-4045 (9.0 to 11.0% Si)**  
This alloy (melting range: 577 to 590°C) is the most common of the filler alloys. Its properties are between EN AW-4343 and EN AW-4047.
- **EN AW-4047 (11.0 to 13.0% Si)**  
This alloy (melting range: 577 to 580°C) has the highest fluidity because of its extremely narrow melting range (eutectic composition). EN AW-4047 flows rapidly on melting and is the most aggressive at dissolving the core alloy. Because of these properties, it is not used as a cladding alloy, but rather as filler wire in flame and induction brazing applications where these properties are in fact desirable.

Typical brazing filler alloys for CAB brazing are EN AW-4045 and EN AW-4343. For vacuum brazing, modified versions with up to 0.5% Mg (e.g. EN AW-4046 or EN AW-4747) are used.

The usual method of applying filler metal is to use a brazing sheet which consists of a core of aluminium clad with the lower melting filler metal. The cladding may be applied to one or both sides of the core sheet, usually making up 5% to 10% of the total thickness of the brazing sheet. The filler metal melts and flows during the brazing process, providing upon cooling a metallic bond between the components. However, filler metals can be supplied in the form of powder, paste, and wire or thin-gauge shim stock and are either face-fed or pre-placed in the joint area. For these product forms of the brazing filler metal, wetting and metal flow phenomena may be quite different in detail. The following discussion, however, refers generally to the application of clad brazing sheets.

Additions of Ti and Cu to braze filler alloys and alloy cladding can improve the overall joint properties without significantly altering the brazing characteristics. Ti increases the corrosion resistance of the brazing alloy on clad materials, while Cu (and Mn) can provide electrochemical corrosion protection and increase strength in critical areas. Furthermore, elements such as Zn, Sn and In may be added to specific areas of an assembly, designed to act as a local sacrificial anode.

Improvements in corrosion resistance centre around the use of Zn or Zn alloy coatings and their application routes. Alloys principally containing Cu and Ni additions (plus Zn) have also been developed for flux-less inert gas brazing down to 520°C.

Recent developments for filler metal alloys focus on the control of fluidity and flow pattern. By adding specific trace quantities of alloying elements (e.g. Na or Li), brazing characteristics may improve. These effects appear to be related to a reduced surface tension.

There are also several suggestions for brazing technologies where the filler metal is generated during the brazing cycle from a coating layer on an aluminium sheet or on extruded material ("clad-less brazing"). One method involves a flux mixture which also contains silicon powder, the NOCLOK® Sil Flux process. At brazing temperature, the elemental silicon reacts with aluminum to melt in a eutectic reaction. Sil flux can be applied with a binder to specific component surfaces, e.g. extruded tubes. In this case, the filler metal would be supplied from the tube and a clad fin sheet is not necessary. In the Composite Deposition technology (CD process), the filler metal for joint formation is derived from a composite powder, a compound consisting of potassium fluoroaluminate flux and an Al-Si alloy. The CD

powder is selectively "deposited" on the heat exchanger components prior to assembly and brazing.

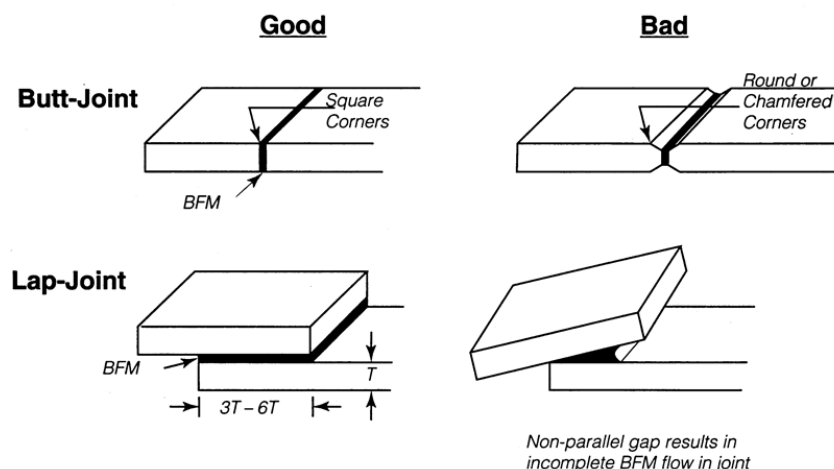
## 6.2.3 Joint design and assembly

In order to enable a most effective capillary action, a suitable clearance between the base metals is necessary. This means that in almost all cases, close geometrical tolerances have to be guaranteed for the single components as well as for the fixed mechanical pre-assembly.

There are basically two types of joint designs used in brazing: butt joints and lap joints. All other joint designs are modifications of these two. Lap joints increase the joint strength by providing additional brazed surface area and section thickness. They are easily fabricated and require minimal or no fixing before brazing. Butt joints are not as strong as lap joints, it should always be assumed that a brazed butt joint will be weaker than the base metal. A variation of the butt joint known as a "scarf" joint (where the two members have tapered ends which lap together) adds strength, but is more problematic to prepare and fixture. Another variation combines the advantages of both joints and is referred to as a "butt-lap" joint.

In butt joint design, the ends of the two metal pieces are butted-up against each other. Then, the brazing filler metal (BFM) is either pre-placed between the two parts prior to assembly, or applied along the top edge of the joint after the two parts are already butted together. When the assembly is brazed, the BFM will melt and flow into the braze-joint by capillary action.

Butt joints are usually used where strength requirements are not critical or where the use of a lap joint is not acceptable (e.g. thickness constraints). The main weakness of butt joints is the small braze area, which is limited to the cross-sectional area of the thinner of the two members being joined. Therefore, it is very important that joint edges are squared and parallel. Rounded edges can seriously reduce the effective braze area.



### Brazed joint design

In lap joints, the two parts intended for brazing are simply laid on top of each, and the capillary spacing between the two pieces will comprise the braze joint. The joint strength of a brazed lap joint is a function of overlap distance and the thickness of the brazed joint itself. The reasonable amount of overlap is about three times the thickness of the thinner of the two members being joined. Any greater overlap does not contribute to joint strength, and a lower overlap might cause failure in the brazed joint rather than in the base metal. For good joint strength, the faying surfaces of the lap joint should be close and parallel to each other and not mismatched.

When brazing aluminium alloys, the set-up of the individual components with respect to alignment and particularly joint gap is very important. A gap between the two components to be joined is necessary to allow the molten flux to be drawn into the gap and clean and dissolve the oxides and to allow the filler metal to be drawn in freely and evenly. The size of the gap determines the strength of the capillary pull. Larger gap clearances reduce capillary action while smaller gaps may restrict filler metal flow causing discontinuities in the joint. As a guide, when torch brazing fluxed lap joints with more than 6 mm overlap, a joint clearance in

the range 0.25 mm or more is recommended. For shorter overlaps, clearance should be in the range 0.05 - 0.2 mm. For dip and vacuum brazing, gap widths of 0.05 - 0.1 mm are common. In controlled atmosphere brazing, gap clearances of 0.10 mm to 0.15 mm are recommended for non-clad components. Friction fits must be avoided with non-clad components. For clad components, the clearance is provided by the thickness of the cladding layer and so intimate contact (gap width < 0.05 mm) is recommended.

### 6.2.4 Cleaning before brazing

For the majority of brazed products, assembly is followed by cleaning and subsequently by flux application. However, when internal surfaces need to be fluxed, the production sequence may follow a different order, determined by when and how the flux is applied.

Brazing uses the principle of capillary action to distribute the molten filler metal between the surfaces of the base metals. Capillary action will work properly only when the metal surfaces are clean. The purpose of cleaning is to remove fabricating oils and lubricants as well as other contaminants (dust and dirt, condensates, etc.). The cleaning procedure must allow for adequate flux retention and render the surfaces suitable for brazing. The effectiveness of the cleaning step has a great influence on the brazing quality, the post-braze product appearance and corrosion performance.

Two techniques are used to clean the components of residual oil and grease:

#### a) Aqueous cleaning

Aqueous or water based cleaning is an efficient and robust process, but generates some waste water. The cleaning solution usually contains a mixture of surfactants, detergents and alkaline ingredients such as carbonates that serves to elevate the pH. The cleaning solution works best at elevated temperatures, i.e. 50 °C to 80 °C. Cleaning takes place in a series of steps starting by dipping or spraying with the hot cleaning solution followed by a series of hot and cold water rinses.

The slightly alkaline cleaning solution has a mild etching action on the aluminium surfaces which causes the aluminium surface to be wettable. This means that the flux slurry will uniformly coat the work piece without the addition of a wetting agent.

#### b) Thermal Degreasing

Thermal degreasing works by elevating the temperature of the work piece so that lubricants present on the surfaces will be evaporated. This procedure only works with special types of lubricants known as evaporative or vanishing oils. These lubricants vaporise when heated to 150 – 250 °C. Lubricants not designed for thermal degreasing must not be used. They could leave behind thermal decomposition products and carbonaceous residues which – at higher level – prevent proper brazing and have the potential to degrade product appearance and accelerate corrosion.

However, thermal degreasing leaves the aluminium surface non-wettable, i.e. the flux slurry requires the addition of a surfactant (wetting agent) to lower the surface tension of the water, thus ensuring more uniform flux distribution.

### 6.2.5 Pre-assembly of the parts

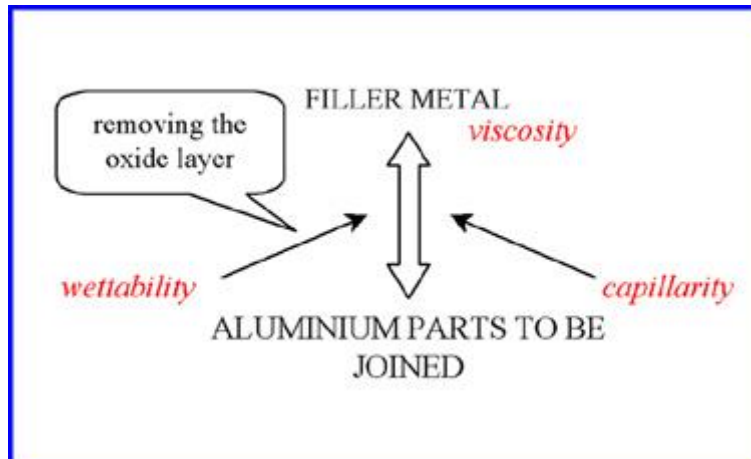
Once the individual parts are cleaned and assembled, they are usually secured in brazing fixtures. Because the yield strength of aluminium alloys decreases rapidly at elevated temperatures, it is often necessary to provide support for components which otherwise could distort under their own weight at the high temperatures necessary for brazing. The brazing fixtures hold the parts together and keep them aligned during the brazing process in order to maintain joint gaps, joint alignment, flow passage alignment, and overall assembly tolerances. Fixtures may also be used to support attachments such as inlet or outlet tubes.

The materials used for the fixtures must be carefully chosen, keeping in mind the different coefficients of expansion of the involved materials. Low thermal mass fixtures reduce the brazing cycle time. Also heat transfer to the fixtures should be minimised to ensure uniform heating. Fixture design is very part dependent and an integral part of the manufacturing process.



## 6.2.6 Brazing fluxes

A most critical aspect is the penetration/removal of the oxide layer. All aluminium surfaces show a thin, but dense and stable oxide layer with a thickness of 2 to 10 nm. The surface oxide layer prevents the filler metal from wetting the aluminium parts to be brazed. Thus the oxide layer has to be removed or broken up prior to the actual brazing step. In the presence of oxygen, however, this oxide layer rebuilds immediately after having been removed, i.e. any rebuilding process must be prevented as far as possible.



In aluminium brazing, flux must be used for every process variant except flux-less inert gas or vacuum brazing. Molten fluxes partially dissolve and remove the oxide layer from the metal surface. The metal surface is cleaned, leaving the surface ideally prepared for the filler alloy to join the metal work pieces. Fluxes also prevent re-oxidation by coating the surfaces to be joined. In addition, by lowering the surface tension, they promote wetting of the base aluminium alloy by the molten brazing filler metal.

The composition of brazing fluxes is selected to fit the specific brazing method. The flux should have a melting point approximately 20 - 50 °C below that of the filler metal and remain stable at least to temperatures 20 - 50 °C above the maximum brazing temperature. It should exhibit minimal reaction or gas evolution at the aluminium surface and should either be non-corrosive or easily removable after brazing. The aluminium brazing fluxes, several different mixtures of alkali, alkaline earth chlorides and fluorides are generally used. Fluoride is the most reactive agent, but its presence increases the flux melting point and therefore other additions, such as Sb, Cd, Cr, Co, Cu, Pb, Mn, Sn and Zn chlorides are often made to control the desired melting temperatures and activity. However, chloride-containing fluxes leave a hygroscopic corrosive surface on the work piece which must be thoroughly cleaned after brazing. The first post-braze cleaning step is immersion of the part into boiling water. Since chloride fluxes are highly soluble in water, this will remove most of the residual flux. Subsequently, an appropriate chemical solution is used. The brazed assembly is then thoroughly rinsed in cold or hot water.

Consequently, fluoride-based fluxes primarily composed of K-Al-F without chlorides are today preferred. The best known chloride-free flux is Nocolok®. Provided that fluoride-based fluxes do not experience an ionising environment, the flux residues are not corrosive and do not need to be cleaned off after brazing. On the other hand, fluoride fluxes require protection by inert gas (generally nitrogen) during brazing. Chloride-free fluoride fluxes do not have to be removed after brazing. In fact, it is generally accepted that the presence of flux residues on a heat exchanger enhances its corrosion resistance.

## 6.2.7 Flux application

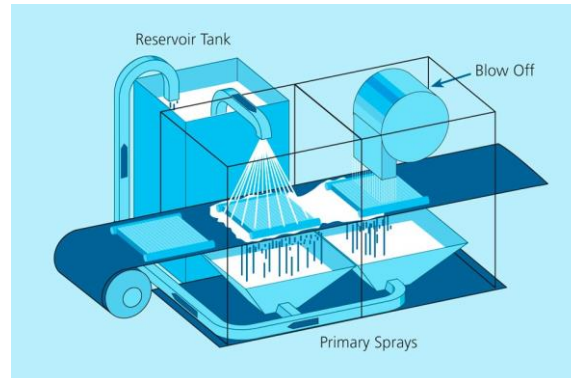
An essential requirement for reliable brazing results is a uniform flux coating on all surfaces involved in the joint formation. Flux can be applied in different forms including flux paste, liquid, powder or pre-made brazing pastes that combine flux with filler metal powder. Flux can also be applied using brazing rods with a coating of flux or a flux core.

Brushing is an effective method of applying a thin film of brazing paste to the joint and to surrounding component surfaces. Brazing flux may be also applied by dipping one or more components of an assembly into a container of flux. This is most effective when using a paste of a thin consistency.

Two application techniques are generally used for larger series production:

### a) Wet flux application

Spraying an aqueous suspension is the most common flux application method for controlled atmosphere brazing. All aluminium surfaces are coated with the slurry, resulting in a uniform flux layer. Excess flux slurry is removed with a high-volume air blow; the excess is then collected, recycled and reused.



### Wet flux application (schematic)

(Source: Solvay)

Constantly agitated flux slurries with concentrations of approximately 10 - 35 % solids are pumped from tanks to fluxing booths. The relatively plain header surfaces generally hold less flux slurry. Most fluxing stations are therefore designed with two flux slurry concentrations to ensure sufficient coverage in the header area by applying a 10 to 15% higher slurry concentration.

Capillary effects throughout the unit can result in a non-uniform flux distribution. Flux slurry tends to be held in fin/ tube joints, fin louvers, etc. Slurry also collects on the bottom surface in those areas that do not see direct air impingement. Excess flux slurry can be blown off from the bottom and side surfaces by installing a second overhead blow-off system or additional air knives for cutting off droplets.

In practice, the recommended loading for fluxing is 5 g/m<sup>2</sup>, uniformly distributed on all active brazing surfaces. Too little flux will result in poor filler metal flow, lower joint quality, higher reject rates and inconsistent brazing. Too much flux will not affect the brazing results. However, the excess flux is wasted and will increase process cost; it may also contaminate the system as well as the final product.

Work pieces entering the brazing furnace must be completely dry from water introduced via aqueous cleaning or flux slurry coating. Therefore, the pre-assembled components must be dried after wet fluxing prior to brazing in a separate oven. However, the surface temperature of the parts in the drier should not exceed 250 °C in order to avoid formation of high temperature oxides which will affect clad fluidity. At higher temperatures (about 300 °C), the oxide layer thickness increases drastically with temperature and time at temperature, particularly in the presence of moisture.

### b) Electrostatic flux application

Electrostatic fluxing, also known as dry fluxing, is increasingly used as an alternative fluxing practice. In dry fluxing, the flux is electrostatically charged and applied to a grounded work piece. The electrostatic attraction results in the deposition of a layer of flux on the work piece. A typical flux application system consists of a powder feed system, the electrostatic spray gun, the gun control unit, the grounded work piece and finally the flux recovery system.

The advantages of such a system over conventional wet fluxing are obvious. There is no need to prepare flux slurries and no wastewater is generated. In addition, the dehydration

section of the furnace may be eliminated. However, flux adhesion is not as good compared to wet fluxing. The flux also tends to accumulate on the leading edges of the components and it is difficult to coat "hidden" areas (e.g. corners or tubes).

Dry fluxing is most interesting when used in combination with thermal degreasing. In this case, it is possible to completely eliminate or significantly reduce water consumption in the process.

There are also further possibilities for flux application techniques, e.g.:

- **Flux painting**

The use of a flux paint (flux + carrier + binder) allows to pre-flux certain heat exchanger components and is helpful when fluxing of internal components is necessary. There are also different process variations possible depending on whether all heat exchanger components are pre-fluxed or whether only some components are pre-fluxed and conventional fluxing is used on the fin pack, etc.

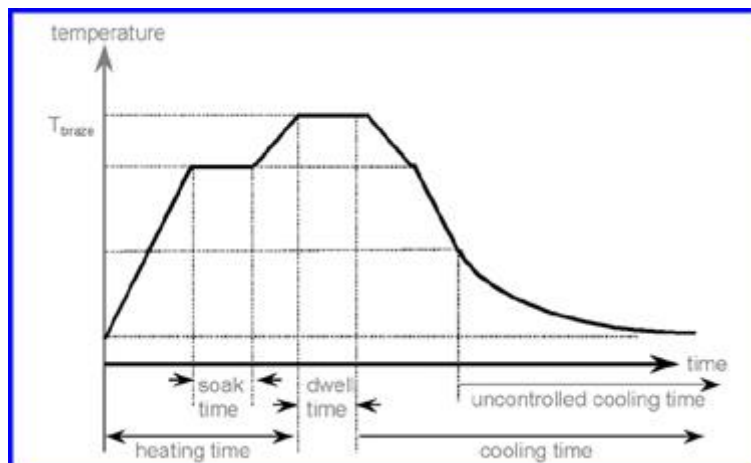
Flux application with a binder system allows coating of specific surface areas with a precise flux amount. It also reduces flux drop-off during assembly. Binders used for pre-fluxing must evaporate during the process without interfering with the brazing performance or leaving any contamination on the surfaces.

- **Flux pre-coated brazing sheet**

The concept of a brazing sheet which is supplied with a flux coating is very plausible. Such a material could significantly change the way heat exchangers are currently manufactured since the flux application step would be eliminated. The greatest challenge is the adherence of the flux to the metal surface throughout the forming process of the components. Uniform coverage and strong adhesion are equally important.

### 6.2.8 Brazing cycle

The main step in the brazing process is the brazing cycle itself. Because of its direct influence on the final product, the time-temperature cycle has to be carefully adjusted. Equally important are the furnace conditions, i.e. temperature profile, temperature uniformity, and atmospheric conditions.



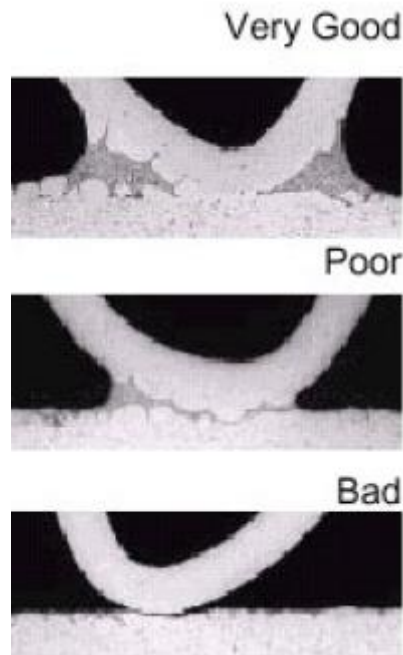
**Brazing time-temperature cycle (schematic)**

Achieving an even brazing temperature distribution throughout the work pieces is a most important factor. Slow heating would ensure even temperature distribution. On the other hand, diffusion processes are facilitated and too slow heating can dry out the flux, reducing its effectiveness. There must be sufficient molten flux present when the filler metal reaches its melting point. As a rule, the heating cycle should be as fast as possible to achieve stable temperature distribution. In industry, heating rates up to 45 °C/min in the range of ambient to 500 °C are not uncommon.

During heat up, there may be quite a variation in temperature across the pre-assembled product. However, it is essential to aim for temperature uniformity when approaching the

maximum brazing temperature and this becomes increasingly more difficult with fast heating rates. At brazing temperature, it is recommended that the variation should not exceed  $\pm 5$  °C. This can be difficult when larger units are processed which have differing mass areas within the product.

The brazed product should not remain at the maximum brazing temperature for any longer than 3 to 5 minutes. The reason is that filler metal erosion begins to take place as soon as the filler metal becomes molten. The longer the filler metal remains molten, the more severe the erosion is. Severe dissolution of the core metal is also caused by excessive brazing peak temperature. Consequently, the brazed products should also be cooled in a controlled manner.



**Good and bad brazed joints in an aluminium radiator**

### 6.3 Soldering

The term “soldering” actually describes a brazing operation using a molten filler metal with a melting temperature below 450 °C. On cooling, a metallurgical joint between the two parent metals is formed. The mechanical characteristics of the joint are reasonably good and thus soldering can be used for example for structural repairs.

Aluminium soldering is not difficult, but shows a number of critical areas that need tight process control. The tenacious aluminium oxide surface layer makes most attempts to solder using conventional means difficult. In addition, care must be taken regarding alloy choice due to possible galvanic corrosion effects as a result of the significant differences between the electrochemical potential of aluminium and that of many conventional solders. The varieties of aluminium alloys, gauges, and tempers often display widely varying soldering results, and the heating procedure during soldering must be carefully optimised for each individual job.



**Repair soldering of a hole in an aluminium pipe**

### 6.3.1 Soldering alloys

Soldering of aluminium components can be done with either soft solders (usually tin-based alloys with lower melting temperatures) or hard solders (zinc-based with higher melting temperatures) and with appropriate fluxes to fit processing temperature ranges. In the past, also lead- and cadmium-based soft solders have been used. However, with the anticipated worldwide ban on lead for environmental reasons, most industries have already or are switching to lead-free solders. Cadmium-bearing solders have been effectively banned due to worker health issues. This eliminated some of the more ductile and/or higher-temperature soft solders which were used in the past for aluminium soldering. Furthermore, any solder that contains tin may cause electrochemical corrosion problems due to its galvanic potential.

A eutectic formulation has advantages when applied to soldering: there is no plastic phase and it has the lowest possible melting point. Having the lowest possible melting point minimizes heat stress during soldering and having no plastic phase allows for quicker wetting as the solder heats up, and quicker setup as the solder cools. A non-eutectic solder formulation should remain immobile as the temperature drops through the liquidus and solidus temperatures. Any movement during the plastic phase may lead to the formation of cracks, resulting in an unreliable joint. Unfortunately, most lead-free solders are not eutectic formulations, making it more difficult to create reliable joints.

Specifically developed tin-zinc alloys for soldering aluminium to aluminium and /or copper parts with good strength and corrosion resistance include:

- 91 % Sn / 9 % Zn (KappAloy9™), eutectic alloy with a melting point at 199 °C
- 85 % Sn / 15 % Zn (KappAloy15™), melting range between 199 and 260 °C.

The eutectic solder is used extensively in furnace soldering and other automated soldering systems. It minimizes the heat applied to delicate parts by melting and solidifying quickly and evenly at 199 °C. In hand soldering, the KappAloy15™ gives more flexibility. The slushy temperature range allows a manipulation of the parts before the solder solidifies completely during cooling. Also used are the solders:

- 80 % Sn / 20 % Zn with a melting range between 199 and 288 °C
- 70 % Sn / 30 % Zn with a melting range between 199 and 316 °C
- 60 % Sn / 40 % Zn with a melting range between 199 and 343 °C.

The higher Zn content improves in particular the wetting behaviour, but the liquidus temperature increases significantly with increasing Zn content.



The other important family of aluminium solder alloys (“hard solders”) can be found in the zinc-rich corner. These solders offer excellent wettability of aluminium, good strength and corrosion resistance. Typical hard solder compositions are:

- 100 % Zn (pure Zn with a melting point of 419 °C)
- 95 % Zn / 5 % Sn (melting at about 382 °C)
- 70 % Zn / 30 % Sn (melting range 199 to 376 °C)
- 60 % Zn / 40 % Sn (melting range 199 to 341 °C).

Also used are zinc-rich Zn-Al solders, e.g. the alloy 95 % Zn - 5 % Al which melts at about 382 °C. Other alloys in the Zn/Al family include 98Zn/2Al, 90Zn/10Al, and 85Zn/15Al.

Recently, solder compositions in the Sn-Ag-Ti system have also been developed for low temperature (250-480 °C) flux-less soldering of aluminium and aluminium alloys.

### 6.3.2 Solderable aluminium alloys

Various aluminium alloys show different solderability: alloys from the systems EN AW-1xxx, 2xxx, 3xxx, 4xxx, and 7xxx are easier to solder than the 6xxx series alloys. Due to their magnesium content, EN AW-5xxx series alloys are most difficult to solder. The magnesium oxide rebuilds very quickly and does not allow solder wetting to take place.

In special cases, an aluminium alloy can be clad with a more solderable alloy, plated with nickel, or coated with zinc for improved soldering performance. Soldering aluminium to other metals (steel, galvanized steel, stainless steel, copper, brass, etc.) can also be done, but with some difficulty, since the joint design must allow for differential thermal expansion and many fluxes do not work for both metals. In addition, heating of the assembly at the joint area may become difficult since aluminium conducts heat away from the joint very rapidly compared to most other metals.

Soft solders do not pose much of a risk to the base materials, provided the parts are not held at soldering temperatures for an extended period of time. However, in some cases, exposure of aluminium to a molten zinc alloy (hard soldering), even for a short time period, may result in the diffusion of zinc atoms into the base metal. This may change the local material characteristics and cause for example heat cracks that emanate beyond the heat affected zone.

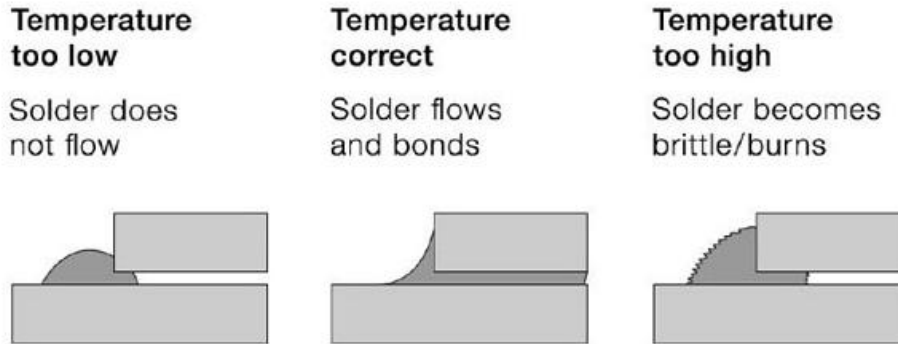
### 6.3.3 Soldering process

Soldering aluminium requires special solders and processing to achieve a solid bond. Breaking the oxide coating by agitation and fluxing is essential for successful soldering. It is important to follow these steps in a timely uninterrupted sequence. Otherwise, the strong oxide coating can rebuild and hinder the solder bond.

By definition, soldering is a low-temperature joining process. Typical soldering temperatures are between 225 and 450 °C. Therefore, less heat distortion of the aluminium component can be expected by soldering than by brazing, welding, or other fusion joining processes. Residual internal stresses in the aluminium work piece from preceding operations, however, can be changed by the heating encountered during soldering, and distortion may result. Therefore, preheating of the components, non-continuous joints, and careful selection of joint geometry may become critical success factors

Aluminium soldering methods generally involve mechanical rubbing with active solders, ultrasonic bath soldering, thermal spray soldering (no use of fluxes) and heating the assembly e.g. by a propane torch, infrared light, laser or within a furnace (all of which usually involve the use of fluxes). Furthermore, it requires an adequate volume of heat on the component and not on the solder. This allows the substrate to transfer heat to the solder and proper melting of the solder.

## THE ALUMINIUM AUTOMOTIVE MANUAL



### Temperature control, a most important quality criteria

Fluxes are used for removal of the oxide layer, to prevent re-oxidation and to facilitate wetting the aluminium. Removal of aluminium oxide requires strong fluxes such as organic amine-based fluxes (up to 285 °C) or inorganic fluxes (chloride or fluoride up to 450 °C). The residues of some soft soldering fluxes may be still active after soldering and must be removed.

The soldered joint is only as strong as the solder material. The surface of the solder seam is smooth and clean, forming a nicely curved transition to the work piece. In general, solder seams do not require finishing.

Soldering of aluminium has never been considered as a mainstream process for the automotive industry although it could be a very attractive joining method with little heat distortion due to the lower process temperature compared to brazing and fusion welding. Soldering requires adequate heat on the component. Because of the high thermal conductivity and reflectivity of aluminium, it has been found that neither soldering with an oxy-acetylene flame torch, plasma arc, laser, induction heater, nor thermal spray is capable of providing good results. Preliminary tests with a high density infrared source (300kW plasma lamp) have shown that proper joints can be produced for EN AW-6xxx alloys using an 80 % Zn - 20 % Al solder with flux at a soldering temperature of 490 °C. Mechanical tests showed that the joint area is stronger than the parent material with minimum softening. However, further optimization would be necessary before introduction into series production.