EAA Aluminium Automotive Manual – Joining

2. Characteristics of aluminium in fusion welding

Content:

2. Characteristics of aluminium in fusion welding

2.0 Introduction

Fusion welding of wrought and cast aluminium components is a key joining technology in automotive engineering. Fusion welding is characterised by partial melting of the work pieces to form a molten metal pool that solidifies and results, after subsequent cooling, in a firm joint. For quality reasons, a filler material is added sometimes. Different energy sources are used to produce the weld, including electricity, laser, electron beam and friction. Various fusion welding processes have been adapted or specifically developed for fusion welding of aluminium which are described in subsequent chapters:

- 3. Arc welding
- 4. Beam welding
- 5. Resistance welding
- 6. Brazing
- 7. Solid state welding.

The present chapter considers some general aspects of the various fusion welding methods.

In order to achieve sound and efficient weld joints of aluminium parts, the choice of joint design, welding parameters, procedures and processes must consider:

- Welding characteristics of the alloys to be joined
- Characteristics of the applied fusion welding process
- Joint configuration and surface characteristics of the joining zone (weld preparation).
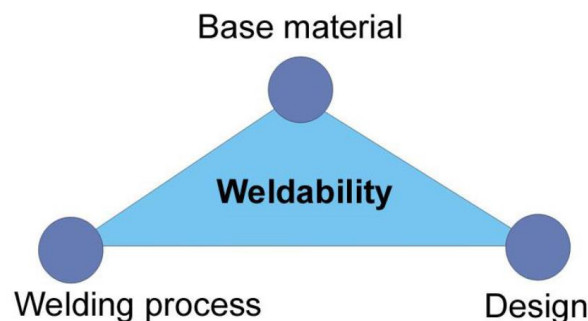
Weldability – a system approach

Weldability, i.e. the suitability of an aluminium part or component for welding, depends on:

- Base material quality (alloy composition, surface characteristics, ...)
- Design (suitability of design for welding, joint design, ...)
- Welding process (welding method, equipment, processing parameters, ...).

2.1 Welding of aluminium

Aluminium and its alloys are in general highly suitable for fusion welding. However, although many welding methods are possible, only selected fusion welding techniques are generally used in series production. Application-oriented refinements in welding tools, equipment and materials have resulted in the increasing acceptance of specific fusion welding methods for aluminium joining.

The physical properties of a material have a significant influence on the welding characteristics:
- Pure aluminum has a melting point of 660 °C, whereas the fusion range of the most common aluminium alloys is between 520 – 660 °C. Because there is no visible color change, it is difficult to judge when the metal approaches its melting point.

- Preheating may be necessary, particularly where thick sections are encountered. A comparison with steel shows a much higher thermal conductivity, a higher heat capacity, heat of fusion and thermal expansion. As a consequence, aluminium materials require high heat inputs to melt and may suffer from large deformations.
- When exposed to air, aluminum rapidly develops a tenacious surface oxide film, which − above all other factors related to aluminum welding − causes the most trouble. Unless the oxide film is destroyed or removed before and during welding, it will interfere with the coalescence of the work pieces and, if applicable, the filler material.

Aluminium alloys that are referred to as „non-weldable" have – as a consequence of their composition − an elevated tendency to solidification cracking and, in some cases, also an increased susceptibility to stress corrosion cracking in the as-welded condition. The following groups of "non-weldable" aluminium alloys are typically mechanically fastened and/or adhesively bonded rather than fusion welded:

- **Aluminium machining alloys**

In many of these alloys, bismuth, tin, and/or lead are added in small quantities to facilitate machinability. The addition of low melting point metals seriously increase solidification cracking tendency. It must be noted that as a result of recent regulations, the addition of lead has been largely discontinued, specifically for automotive applications.

- **EN AW-2xxx series alloys containing aluminium-copper-magnesium**

These alloys which are used for aerospace and other high performance applications can be susceptible to solidification cracking as well as stress corrosion cracking and premature failure after fusion welding. However, binary aluminium-copper alloys of the 2xxx series are considered to be weldable when using an Al-Cu filler metal.

- **EN AW-7xxx series alloys contaning aluminum-zinc-copper-magnesium**

If these alloys (also used for aerospace and other high performance applications) are fusion welded, they may also fail for the reasons outlined above. Alloys based on the aluminium-zinc-magnesium system without copper, however, are considered to be weldable.

In the heat affected zone of the "non-weldable" EN AW-2xxx and -7xxx series alloys, low melting point intermetallic phases are preferentially precipitated at the grain boundaries which lowers and widens the solidification temperature range of the grain boundary. Consequently, when arc welding these types of base metals, the grain boundaries become the last to solidify and can easily crack due to solidification shrinkage stresses. In addition, the difference in galvanic potential between the grain boundaries and the interior of the grains is increased, making them more susceptible to stress corrosion cracking.

2.1.1 The aluminium oxide film

The thickness of the oxide layer covering technical aluminium surfaces is smaller than 0.01 mm. The melting point of aluminium oxide is about 2000 °C, in contrast to 660 °C of the aluminium metal. Due to its high melting point, the oxide film does not dissolve in the weld bath, but must be (locally) destroyed to obtain a fused bond line in the joint. The aluminium oxide film is relatively strong, it has a low electrical and thermal conductivity and can easily cause welding defects. In general, it shows an inhomogeneous structure and rough surface with a high affinity for gas adsorption and surface contamination, i.e. it is a potential source for gas porosity. Furthermore, the oxide density is higher than the density of molten aluminium and may form non-metallic inclusions in the fusion zone.
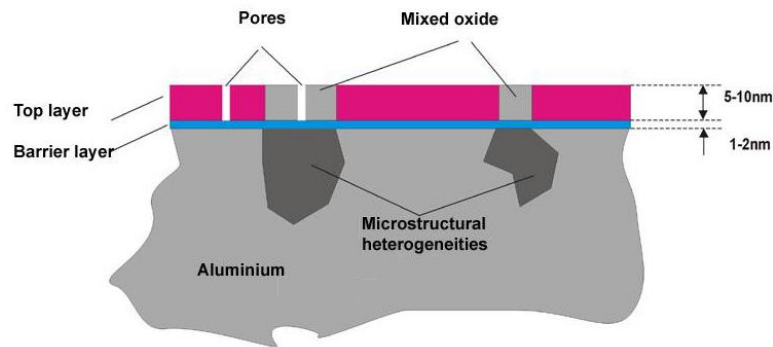
Constitution of oxide layer on aluminium alloys (schematic)

In order to form a proper weld, the oxide film has to be removed or cracked during the welding process to allow the fusion of the metal. This can be facilitated by the application of an appropriate surfaces treatment before welding. Proper cleaning of the aluminium surface is always necessary in order to achieve high quality welding results (see also 9.4).

Nevertheless, even after complete removal of the original oxide film, aluminium surfaces are immediately re-covered by a thin oxide film. Destruction of this oxide film is achieved for example in arc welding techniques by the cleaning action of the electric arc and of the shielding gases. Oxide removal is essentially caused by ion impingement and little (if any) by electron penetration through the oxide barrier. The efficiency depends on electrode polarity and is therefore influenced by the type of current:

- Positive electrode → cracking of the oxide film by ion impingement,
- Negative electrode → no oxide film removal by ion impingement.

In contrast to argon, helium provides also some cleaning action with negatively poled electrodes because of its higher ionisation energy and higher heat dissipation.
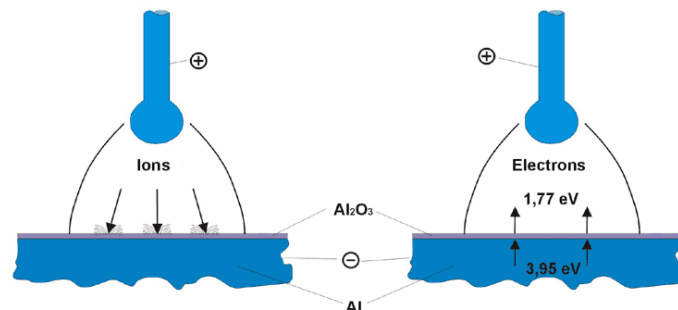
Removal of aluminium oxide by ion impingement (left) and electrode penetration through the oxide layer (right)

2.2 Weld preparation

The production of high-quality fusion welds between aluminium components depends strongly on the quality of the surfaces to be welded. Special care is required to limit porosity and other internal imperfections of the weld zone. The most important factors are:

- Correct storage of components, work piece, filler materials (dry as well as smut-, oil- and dust-free environment)
- Minimize moisture condensation and absorption of water contamination during transport and storage
- Proper surface preparation of the areas to be joined, avoid ground or smeared surfaces.

The level of cleanliness and metal preparation required for welding depends on the desired weld quality level. Dirt, oil residues, moisture and oxides must be removed, either with mechanical or chemical methods. Surface films containing hydrogen bearing mixtures

represent the largest problem because they are broken down into atomic hydrogen in the arc, causing gas porosity in the weld. Normal shop practice is to mechanically remove the oxide layer by brushing, scraping or shot peening. Only light pressure should be used when brushing. Excessive pressure might lead to locally overheating and distortion of the metal surface.

Applicable chemical treatments include cleaning with alcohol or acetone, alkaline or acidic pickling or even more complicated chemical treatments. As an example, the amount of porosity in the weld seam decrease as result of the applied preparation technique of the joint surface in the following order:

- As-received state (sheared, plasma arc cut or laser cut)
- Milling
- Grinding
- Brushing with rotating CrNi steel brushes
- Etching
- Etching and scraping (only joint surface).

In critical applications, the cleaned surface produced by etching may be subsequently protected by a suitable conversion treatment. A suitable conversion treatment of the individual components ensures ideal welding conditions. However, this additional process step is generally not necessary provided that the components are properly stored and handled before welding.

2.3 The welding zone

Fusion welding produces a locally modified microstructure. Different zones can be identified as a result of local alloy composition changes and/or the temperature cycle during welding. Depending on the actual heat input and the geometry of the joint, the width of these zones can vary considerably.
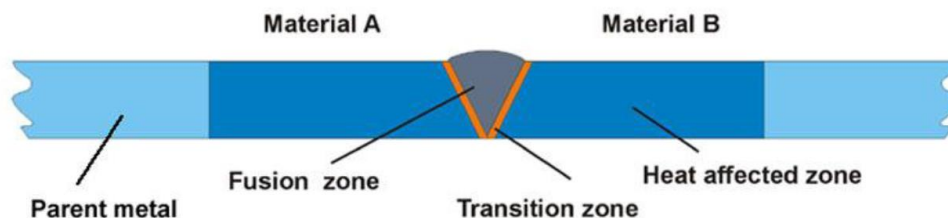
Characteristics of the welding zone

The **fusion zone** is characterised by the presence of molten metal from both adjoin materials A and B and, if applicable also from the introduced filler metal. The solidification of the molten metal pool starts from the weld seam.

In the **transition zone**, (partial) melting of the eutectic phases at the grain boundaries will take place. Also, diffusion of alloying elements along the grain boundaries may occur.

In the **heat affected zone**, thermally controlled solid state processes (segregation effects, precipitation processes, recovery and recrystallisation processes) are possible, depending on the reached temperature level.
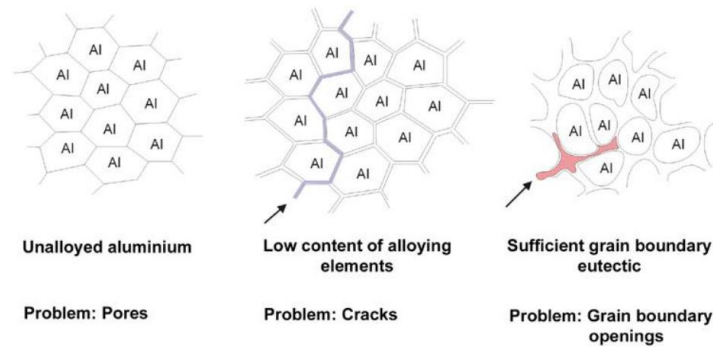
2.3.1   Solidification in the fusion zone

Solidification in the fusion zone is generally characterised by rapid cooling and solidification processes, i.e. a fine as-cast grain structure is formed. The resulting grain size can be controlled by an appropriate selection of the welding parameters.

Three types of weld pool solidification are being observed, i.e. without eutectic formation (pure aluminium), with a low fraction of grain boundary eutectic (in general with low alloyed aluminium alloys) and with a continuous grain boundary eutectic (i.e. for highly alloyed

aluminium alloys). As a result of these different types of solidification, there are various potential defects which form at the grain boundaries.

Unalloyed aluminium

Problem: Pores

Low content of alloying elements

Problem: Cracks

Sufficient grain boundary eutectic

Problem: Grain boundary openings

Solidification types of aluminium alloys

2.3.2 Crack formation in the fusion zone

Depending on the specific welding conditions (design, applied welding process and material combination), there is a risk for crack formation in the fusion zone. An important factor influencing the cracking sensitivity is the solidification range of the particular alloy (temperature difference between liquidus and solidus).

The risk for crack formation ("hot cracking") in the fusion zone increases with increasing solidification range of the alloy (or the alloy combination) to be welded:

- Pure aluminium has no solidification range and is resistant to cracking.

- Non-age hardening alloys (EN AW-1xxx, 3xxx and 5xxx series) have solidification ranges below 50 °C and can be readily fusion welded provided the necessary measures are taken.

- The solidification ranges of EN AW-6xxx series alloys and 7xxx alloys of the Al-Zn-Mg system are about 50 °C and are thus sensitive to solidification cracking. Proper countermeasures are necessary to ensure an adequate weld quality.

- In general, high strength alloys containing copper and magnesium as well as zinc (some EN AW-2xxx serie and 7xxx alloys) have solidification ranges larger than 100 °C and therefore show a high cracking sensitivity. Fusion welding is very difficult, if not impossible.

Solidification cracking is the result of the presence of high thermal stresses and the solidification shrinkage effect as the weld pool solidifies. It is determined by a combination of metallurgical, thermal, and mechanical factors. In practice, the cracking sensitivity within the fusion zone can be reduced by the use of a filler wire. The addition of the filler wire allows changing the alloy content in the fusion zone to an uncritical alloy concentration. If the correct filler metal is selected, the cracking can be avoided. Another way to reduce solidification cracking is to reduce transverse stress or to increase the amount of edge preparation.

As an example, two strategies to compensate the weld cracking propensity in Al-Mg-Si alloys are shown in the following figure:
- Alloying with Mg (R-5056A)   (possibility A)
- Alloying with Si (R-4043A)   (possibility B).
Under the assumption of a 50% mixture of parent and filler metal in the weld pool, the graphic indicates a significantly decreasing tendency for crack formation.
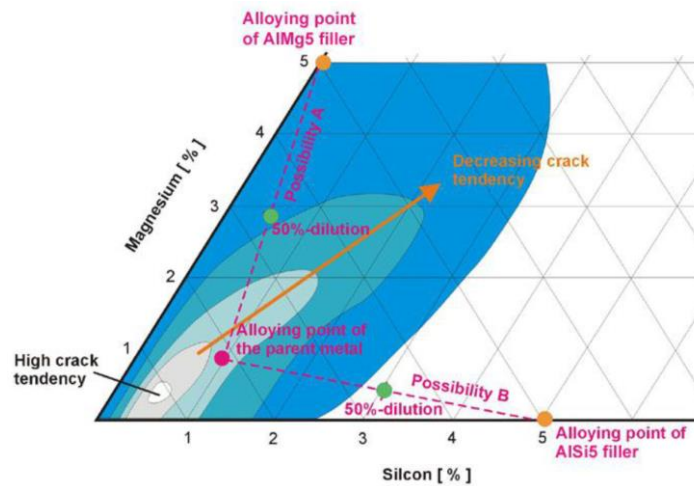
Weld cracking propensity in Al-Mg-Si alloys

Another type of cracking in fusion welded, precipitation hardenable aluminium alloys is liquation cracking. Liquation cracking may occur in the transition zone when the temperature is increased sufficiently above the melting point of low melting eutectic intermetallic phases present at the grain boundaries. A crack will develop if there is sufficient tensile stress in the joint and the molten eutectic may connect to the fusion zone. The combination of solidification shrinkage and insufficient molten metal feeding may then prevent the closing of the formed crack when the weld solidifies.

Higher heat input tends to expand the affected region. Therefore, the selection of filler alloy with a lower solidification temperature and improved fluidity will provide lower susceptibility to liquation cracking since the solidification shrinkage occurs at a lower temperature. Similarly, lower thermal input with higher current or higher travel speed can also mitigate this problem. Additionally, designing joints that improve filler metal dilution into the base material and mitigate solidification stresses will also decrease the sensitivity for crack formation.

A third type of cracking is due to alloy segregation where the centerline of the weld pool solidifies last due to solute segregation. This is similar to liquation cracking and can manifest itself as "crater cracks" that are star shaped in the center of the weld. Assuring proper filler metal dilution and applying techniques where additional wire can be fed into the weld, will reduce the susceptibility for segregation based cracking.

2.3.3 Gas absorption and pore formation

Pores caused by hydrogen are a characteristic phenomenon observed when welding aluminium and its alloys. The reason for the formation of hydrogen porosity during solidification is the ability of liquid aluminium to absorb a large amount of hydrogen. During solidification, the hydrogen solubility decreases by a factor of 20. Thus the excess gas is released and the hydrogen bubbles may become trapped and forms pores.

Depending on the solidification morphology of the alloy, two types of hydrogen porosity are observed:

- Pores distributed uniformly,
- Pores linked together in a chain-like fashion.

Low welding speeds (and high energy input) lead to a broad fusion zone and, as a result of the lower solidification rate, to an unfavourable porosity distribution.
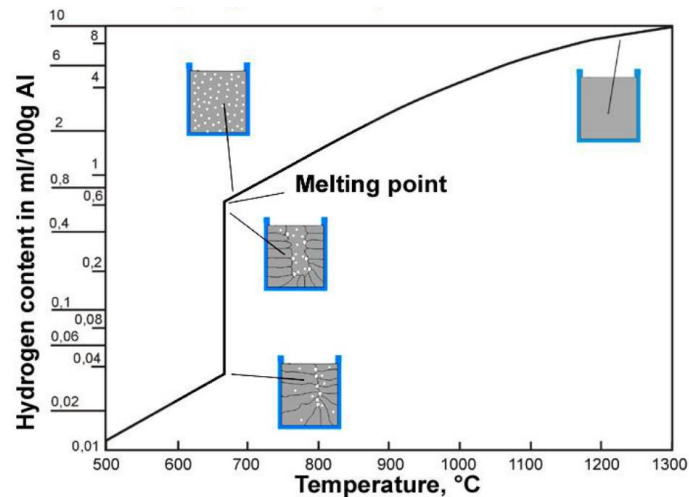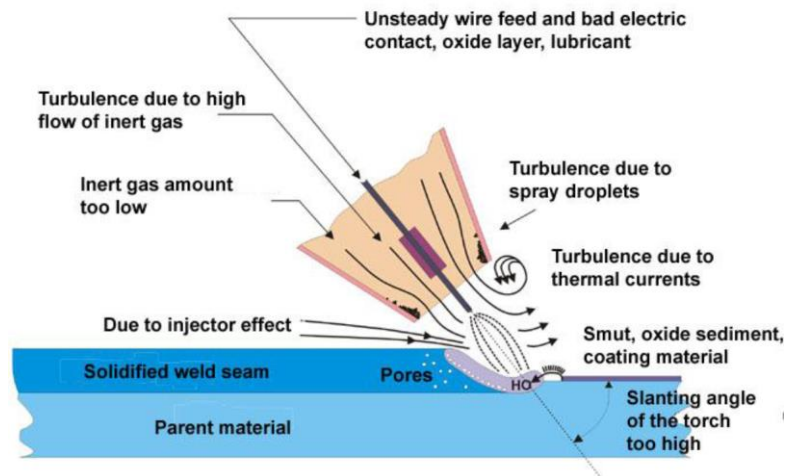
Hydrogen gas absorption during welding

The high solubility of molten aluminium for hydrogen leads to the absorption of additional hydrogen in the molten metal pool during welding. Hydrogen may originate from moisture and contaminants (e.g. dirt, oil and grease) on the work pieces or the welding equipment (incl. filler wire) and the shielding gas or the surrounding atmosphere. Hydrogen and other gases causing porosity are absorbed by:
- Turbulences in the shielding gas envelope; the reason can be a too high or too low flow rate of the shielding gas.
- Unstable arc conditions,
- Unfavourable torch position, too high slanting angle,
- Entrance of air into the shielding gas nozzle,
- Impurities on the work piece surface, filler wire, or in the used shielding gases,
- Insufficient edge preparation.

Gas absorption during welding

2.4 Filler materials

Filler metals are generally introduced in the form of wires. The addition of filler metals has two goals:
- To avoid the formation of cracks in the fusion zone through an adjustment of the alloy composition of the molten pool
- To provide additional material for gap bridging.

Therefore, filler wire alloys have to be adapted to the alloy compositions(s) of the components to be welded and the required strength and formability (as well as other properties) of the weld zone have to meet the product requirements for the final assembly.

The composition of the most important filler metals for aluminium welding belong to the two groups:

− Si or Mg are the main alloying elements
− Depending on the specific alloy (combination), varying amounts of other elements (e.g. Mn, Cr, Ti and Fe) are used.

Filler metals based on the composition AI – 5 % Mg generally provide welds of the highest strength. On the other hand, filler metals based on AI – 5 % Si are more resistant with respect to solidification cracking and easier to use when welding age hardenable alloys.

Little development work has been done during the last decades to develop filler metals for aluminium welding. A heightened interest has been shown only during recent years due to the increased amount of welding performed on aluminium. Newly developed filler metals offer increased strength and reduced mismatch, which in turn reduces material consumption and enables new possibilities in design.

2.4.1 Selection of filler materials

Depending on the specific welding technique and material combination, the application of a filler wire is not necessary. However, if a filler wire is being used, it is most important to select the proper filler metal composition. The main factors which influence the filler alloy selection are:

- Prevention of hot cracking
- Weld metal strength and ductility
- Corrosion resistance
- Weld performance at elevated temperatures
- Weld metal fluidity
- MIG electrode wire feedability
- Weld metal colour match with base material after anodizing.

The filler metal as such is not hardenable, which implies that no hardening procedure can strengthen the weld after welding. When a good colour match is needed between the weld bead and the surface, Si-alloyed filler metals should be avoided. When anodising, the precipitated silicon particles impart a dark grey, almost black colour.

Choice of filler metal for various aluminium alloys and alloy combinations

(first designated filler is preferred)

Alloy B ╲ Alloy A	AW-1090 / AW-1080A / AW-1070A	AW-1050A / AW-1200	AW-3103 / AW-3003	AW-5005A / AW-5051A / AW-5052	AW-5754 / AW-5019	AW-5454 / AW-5251 / AW-5049	AW-5086 / AW-5083	AW-6060 / AW-6005A / AW-6082 / AW-6061	AW-7020	AC-41XXX / AC-42XXX	AC-43XXX / AC-44XXX	AC-51XXX
EN AW-1090 / EN AW-1080A / EN AW-1070A	R-1080A											
EN AW-1050A / EN AW-1200	R-1050A / R-1450	R-1050A / R-1450										
EN AW-3103 / EN AW-3003	R-1450 / R-3103	R-1450 / R-3103	R-3103									
EN AW-5005A / EN AW-5051A / EN AW-5052	R-5356 / R-3103	R-5356 / R-3103	R-5356 / R-3103	R-5356 / R-5149								
EN AW-5754 / EN AW-5019	R-5356	R-5356	R-5356 / R-3101	R-5356	R-5356 / R-5754							
EN AW-5454 / EN AW-5251 / EN AW-5049	R-5356 / R-3101	R-5356 / R-3101	R-5356 / R-3101	R-5356 / R-5149	R-5356 / R-5754	R-5356 / R-5149						
EN AW-5086 / EN AW-5083	R-5356 / R-3101	R-5356 / R-3101	R-5356 / R-3101	R-5356 / R-5149	R-5356 / R-5754	R-5356 / R-5149	R-5183 / R-5087 / R-5356					
EN AW-6060 / EN AW-6005A / EN AW-6082 / EN AW-6061	R-4043A / R-5356	R-4043A / R-5356	R-4043A / R-5356	R-5356 / R-5149	R-5356 / R-5754	R-5356 / R-5149	R-5183 / R-5087 / R-5356	R-4043A / R-5356				
EN AW-7020	R-5356 / R-5149	R-5356 / R-5149	R-5356 / R-3103	R-5356 / R-5149	R-5356 / R-5754	R-5356 / R-5149	R-5183 / R-5087 / R-5356	R-5356	R-5183 / R-5087 / R-5356			
EN AC-41XXX / EN AC-42XXX	R-4043A	R-4043A	R-4043A	R-4043A	R-4043A	R-4043A	R-4043A	R-4043A	R-4043A	R-4043A		
EN AC-43XXX / EN AC-44XXX	R-4047A	R-4047A	R4047A	R-4047A	R-4047A	R-4047A	R-4047A	R-4047A	R-4047A	R-4047A / R-4043A	R-4047A / R-4046	
EN AC-51XXX	R-5356	R-5356	R-5356	R-5356	R-5356	R-5356	R-5356	R-5356	R-5356	◇◇◇◇◇◇	◇◇◇◇◇◇	R-5356

Selection of filler metal

A major factor towards producing good quality aluminium welds is the use of high quality filler rods and wires of the correct diameter and alloy specification. Moreover, the filler metal surfaces must be kept free from moisture, lubricants, and other contaminants.

2.5 Shielding gases for welding aluminium

The aluminium weld pool as well as the electrode must be protected from the atmosphere. The other role of the shielding gases is to provide a stable arc, to cool the electrode and to minimise the introduction of defects into the weld.

The most important selection criteria is the heat conductivity of the gas. For aluminium welding, the predominantly used inert gas is argon, but also combinations of helium and argon are applied. Effective mixtures have been found to lie between 30 - 70 % of each respective gas (typical mixtures are Ar/He: 30/70; 50/50 or 70/30). Compared to argon, helium offers a higher heat concentration and a higher melting rate, but also heat dissipation is higher and arc stability is lower. Because of its lower density, helium requires a higher flow rate than argon.

The advantages that can be reached with helium are the result of the higher arc power (due to the higher ionization energy of helium compared to argon) combined with its better heat conduction (nine times higher than that of argon). Helium raises the temperature of the arc which increases the heat delivered to the weld and weld zone. As a result, the weld penetration is deeper and broader than with argon, contributing to a reduced porosity in the weld bead. On the other hand, with a good heat transferring gas such as helium, a higher fraction of the heat (generated from the energy converted in the arc) will be lost to the environment. The most common solution is to use argon for MIG and AC TIG welding because the process is usually easier to control with argon.

As welds in aluminium are prone to the formation of oxide inclusions and voids, the shielding gas must meet strict purity requirements. Process gases and gas supply system must be clean and free from moisture because even minute traces of dirt or moisture can cause severe weld porosity. Argon and helium should have a minimum purity of 99.995 % and a dew point of - 60 °C or lower. It is very important that the purity of the gas is preserved all the way to the arc. If there is any leakage in the welding equipment, the gas will be contaminated.

Sometimes monomix shielding gases are used consisting of inert gases with minute amounts of active gases (O_2, CO_2, NO in less than 0.1 vol. %). Very small additions of oxidising components do not adversely affect the weld quality, but actually improve arc stability. They provide a slight, but measurable improvement of the energy transfer and consequently of the welding speed. Monomix shielding gases are also claimed to produce a smoother transition between weld and base metal, thus improving the fatigue properties of welded components. CO_2 is suitable for MIG welding of AlMg alloys, but cannot be used for TIG welding since CO_2 would rapidly destroy the tungsten electrode. The addition of 0.03 % NO can also be used for TIG and MIG welding in order to reduce ozone levels.

2.6 Joint design for fusion welding

The right choice of joint configuration depends on the
−   material thickness
−   accessible torch or beam positions
−   technological requirements
−   clamping possibilities
−   required tolerances.
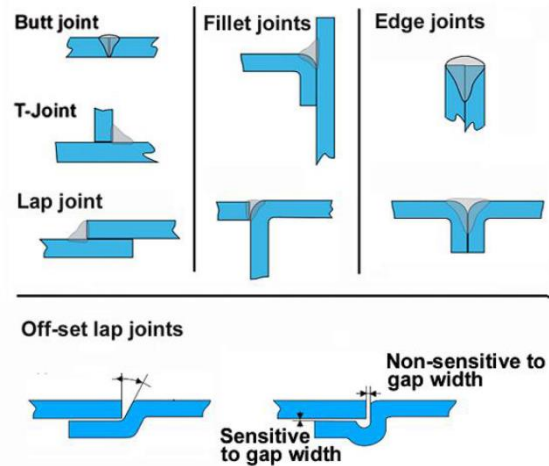
Joints for gas shielded arc welding

The joint configuration must be selected with respect to the principle stresses acting on the joint (i.e. tension, compression or shear loads). Some recommended joint configurations are given below. Shear stress should be largely avoided, because most joints are very sensitive to this kind of loading.
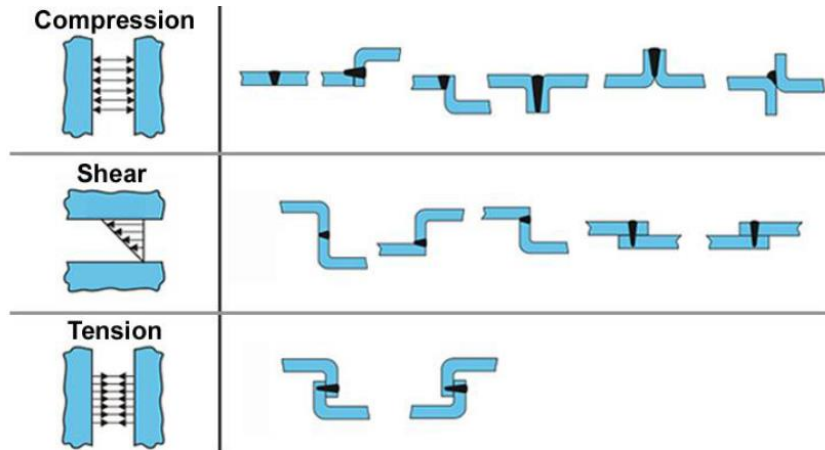
Recommended joint configurations

The aluminium extrusion technology offers some interesting possibilities to simplify the welding process. Examples of innovative, proactive aluminium profile design include edge preparation, material compensation, in-built fastening, integral root backing and the minimisation of the number of welds required are all examples of proactive.

Aluminium profiles can also be designed in a way that reduces the required number of welds. Furthermore, welds can be located in a low stress section of the cross-sectional area. This means fewer welds and improved strength. In addition, butt welds are used rather than the weaker fillet welds.
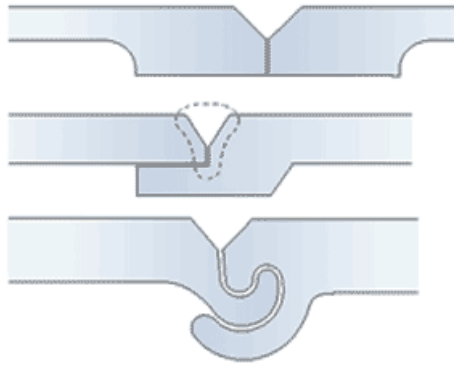
Edge preparation (and material compensation for strength reduction in the weld zone) integrated into the profile design

(Source: Sapa)

Placing welds in lower stress sections of the cross sectional area (left) and reduced number of welds

(Source: Sapa)

When the welding plan (i.e. the order in which the weld are performed) is established, minimum geometrical distortion oft he assembled sructure must be envisaged. The key words In order to reduce geometrical distortions due to shrinkage, low heat input and symmetrical welding must be envisaged. The following recommendations can be made:

- Weld as little as possible.
- Use highly productive welding methods with maximum welding speed and the lowest possible heat input.
- Begin welding in the centre of the structure and proceed symmetrically outwards.
- If longitudinal and transverse joints meet, weld the transverse first. If butt and fillet joints meet, weld the butt joints first.
- Use fixtures that provide even cooling, if possible, allow free movement oft he work pieces.

Even if the above mentioned measures are taken, it may be difficult to get welded parts completely free from distortions. An efficient and long-established method of correcting distorted parts is flame straightening. In flame straightening, an oxy-fuel flame is used to quickly heat a limited area of the component or assembly. For aluminium, the proper temperature range is 350 – 400 °C. Upon cooling, the material in the heated area contracts more than it expanded when heated and the component or assembly is straightened out. By using external restraining devices, the straightening effect can be reinforced.

Other possible measures to reduce thermal distortions during welding include the use of temporary backing strips that are applied to control weld penetration. They are removed after welding. Care must be taken to prevent melting the backing material into the weld pool. In addition, preheating to 100 – 200 °C can be used when welding large material thicknesses, in particular to reduce the thermal effects of the different material cross section when welding work pieces of dissimilar thickness. However, all these measures (flame straightening, temporary backing strips and preheating) add additional complications and should be avoided in series production by proper design of the welded structure and an appropriate welding schedule.

Attention to good joint fit-up (i.e. joint gap/root face combinations and plate mismatch) is important to ensure the production of high quality welds. Joint fit-up and edge preparation are

closely related. Inferior joint fit-up will produce poor welds, independent of the quality of edge preparation.

In addition to edge preparation and joint fit-up, joint accessibility becomes just an as important consideration. The aspect of accessibility (i.e. the sizes of the welding TIG torch or MIG gun and the arcing characteristics) is often overlooked during the initial design stage. Apart from the accessibility factor, the designer should always be aware that it is important to allow an unrestricted view of the arc within the preparation.

2.7 Characteristics of the weld zone

The fusion zone shows an as-cast structure with the respective physical characteristics. Most important in practice, however, are the related property changes within the heat affected zone. Every fusion welding process leads to the formation of a heat affected zone in the neighbouring parent metal where − depending on the original microstructure and the location − different thermally assisted microstructural processes can occur. The extension of the heat affected zone depends on the thermal input, which again depends on:

- the heat input of the specific welding technique,
- the welding speed and - for multi-pass welding - pass thickness, and
- the thermal conduction as determined by the work piece geometry and alloy composition.
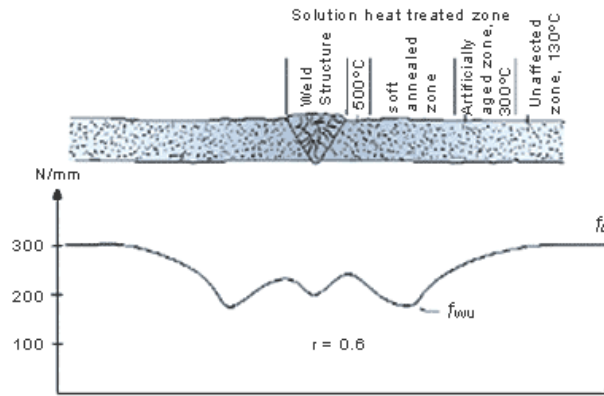
Strength variation in the heat affected zone of a welded Al-Mg-Si alloy

(Source: Sapa)

In general, the heat affected zone is characterised by a local softening (reduction of strength). The resulting strength change depends on the alloy type, the original microstructural characteristics (local strengthening mechanisms) and the active softening mechanisms. In non-heat treatable aluminium alloys, the strength of work-hardened tempers (H tempers) is reduced due to recovery / recrystallisation processes whereas no (or relatively small) strength changes occur for soft (annealed) tempers.

When heat treatable aluminium alloys are welded, they lose a significant amount of their original mechanical properties in the heat affected zone. If the base metal being welded is in the -T4 temper, much of the original strength can be recovered after welding by proper post-weld ageing. If the base metal is welded in the -T6 temper, it can be solution heat treated and aged after welding which will restore it to the -T6 temper. However, any post-weld heat treating and ageing may cause additional problems.

In Al-Mg-Si alloys (EN AW-6xxx serie), the strength of the original T4 or T6 tempers is reduced in the heat affected zone due to over-ageing. Full re-hardening would require a complete solution heat treatment followed by quenching and artificial ageing; as a result, the welded assembly will most likely be strongly distorted. Partial re-hardening after welding is possible up to about 40 % of the parent metal strength. Therefore, it is recommended:

- To keep the energy input per unit length of the weld as small as possible (→ reduce width of heat affected zone),

> − To weld AlMgSi alloys in the T4 temper followed by age hardening of the complete assembly (if possible).

With extruded aluminium profiles, it is easy to compensate for the decreased joint strength by a local increase of the wall thickness. Furthermore, edge preparation can be directly incorporated into the cross section design.

In Al-Zn-Mg alloys (Cu-free alloys of the EN AW-7xxx serie), strength in the heat affected zone is reduced due to the re-solution of the precipitates. In this case, natural or – preferred – artificial ageing allows to restore more or less the original strength. As an example, the weldable EN AW-7020 offers unique possibilities due to:

> − large solid solution range from 350 to 500 °C,
>
> − low quench rate sensitivity,
>
> − significant age-hardening effect at room temperature.

The heat affected zone reaches the original strength after 90 days of natural ageing.

Apart from strength, the corrosion resistance in the heat affected zone is probably the most important issue which has to be considered. As a rule, the heat input caused by the welding process often reduces the standard corrosion properties of aluminium alloys in the weld zone. The area next to the weld and the weld bead may lose corrosion resistance due to the creation of a coarse-grained structure. Furthermore, solidification cracks may promote the corrosive attack since can easily open the cracks. In addition, the potential formation of local residual stresses has to be considered in detail.

Among the "weldable" aluminium alloys, EN AW-6xxx and -7xxx alloys are most sensitive to corrosion problems after fusion welding. Pure aluminium and the non-hardenable alloys are more resistant or are not affected at all.


2.8 Imperfections in fusion welds

The presence of imperfections in a welded joint may not render the component defective in the sense of being unsuitable for the intended application (thus the preferred term is imperfection rather than defect). Welds that contain discontinuities serious enough to affect the weld strength, corrosion resistance or any other characteristic properties are considered as "defective welds". The defects may be the results of incorrect metal preparation, welding procedures or techniques. Common defect types include cracks (longitudinal, transversal or crater cracks), excessive porosity, incomplete fusion, undercuts and inadequate penetration. Incorrect weld size and shape are also considered as weld defects.

Imperfections can be distinguished with respect to their nature:
- Physical   (e.g. cracks in fusion zone)
- Chemical   (e.g. oxide inclusions)
- Geometrical   (e.g. edge misalignment).

In industrial practice, however, imperfections in welds are rather divided into external and internal irregularities.
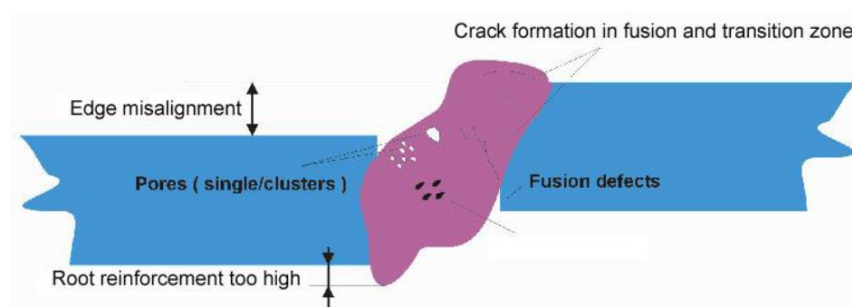
Examples of internal and external imperfections

Imperfections must be considered as irregularities in welded joints and, since they will always be present to some degree, it is necessary to define acceptable limits. There are various standards and guidelines for the description of external (e.g. misalignment of edges, notches and poor weld geometry) and internal (e.g. type and distribution of porosity, inclusions, cracks

and fusion defects) imperfections. The purpose of these standards and guidelines is to allow for a clear description of the observed defects.

The use of standardised terms also enables the establishment of application-oriented consistent quality specifications for welds. A subdivision into different evaluation classes enables the definition of limiting values, depending on the required geometrical tolerance and/or weld characteristics. This is done in appropriate guidance documents.

In design codes for welded structures, the imperfections are broadly classified into those produced during fabrication of the component or structure (external and internal imperfections as defined above) and those formed as result of adverse conditions during service (e.g. brittle fracture, stress corrosion cracking or fatigue failure). The application code will specify the quality levels which must be achieved for the various joints.

Welding procedure, joint features and access and welder technique will have a direct effect on fabrication imperfections.

a) Solidification cracking
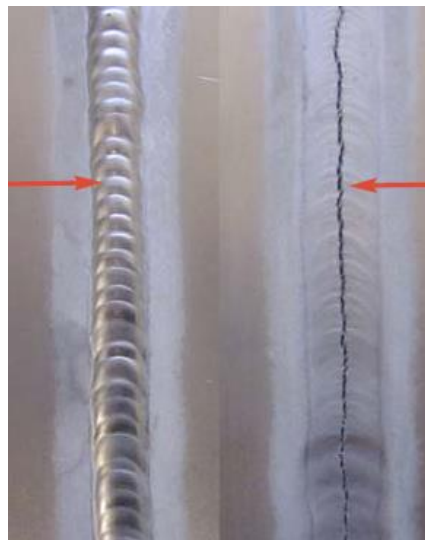
TIG weld of the alloy EN AW-6061-T6 welded with 4043 filler metal (left) and without filler wire (right)

(Source: MAXAL)

The majority of aluminium alloys can be successfully fusion welded without cracking-related problems. Solidification cracking can be considered as a metallurgical weakness (see section 2.3.2), i.e. the result of a non-appropriate use of filler metal (no filler metal or wrong filler wire composition). It can also the result of not appropriately developed and tested welding procedures (e.g. too little filler metal in the weld, too small weld for the base material thickness or too low welding speed).

Solidification cracking (hot cracking) is a high-temperature cracking mechanism and is mainly a function of how metal alloy systems solidify. Aluminium crack sensitivity curve diagrams are a helpful tool to understand why aluminium welds crack and how the choice of filler alloy and joint design can influence crack sensitivity. The crack sensitivity curves show that with the addition of small amounts of alloying elements (Si, Cu Mg), the crack sensitivity becomes more severe, reaches a maximum, and then falls off to relatively low levels.

It can be seen that most of the aluminium alloys considered unweldable autogenously (without filler alloy addition) have chemistries at or near the peaks of crack sensitivity. In these cases, it is important that the composition of the weld, which is comprised of both base alloys and the filler alloy, lies in an area of low crack sensitivity.
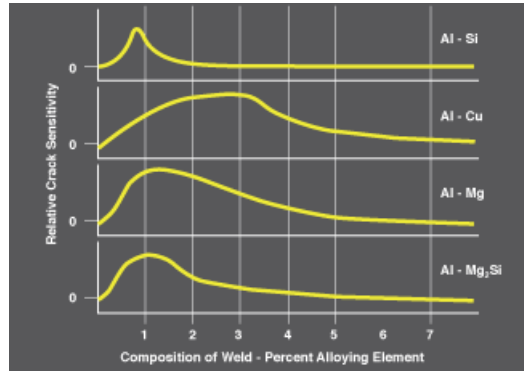
Crack sensitivity curve of the most common weld metal chemistries

A further aspect to be considered are secondary cracking mechanisms. The filler metal choice has an effect on the shrinkage stress. Silicon filler metals (4xxx) have lower solidification and reduced cooling shrinkage rates than Mg filler alloys (5xxx). Therefore, 4xxx filler alloys have lower shrinkage stresses and produce reduced stress cracking.

b) Porosity

Porosity causes much concern despite the fact that, unless it is severe or aligned, it usually has less effect on weld strength than other defects. It is rather easily detected through standard radiography and thus has become a highly regulated defect.
Porosity is generally caused by hydrogen gas trapped in the metal as it cools (see section 6.3.3). The relevant sources of hydrogen that create porosity are:
- Hydrocarbons (in the form of paint, oil, grease, other lubricants and contaminants)
- Hydrated aluminum oxide (aluminum oxide can absorb moisture and become hydrated, the hydrated oxide will release hydrogen when subjected to heat during welding)
- Moisture (moisture within the atmosphere can be a serious cause of porosity under certain circumstances). Moisture from other external sources such contaminated shielding gas or from pre-cleaning operations must also be considered.

To control porosity, it is essential to eliminate moisture and contaminants by correct metal preparation and control of the welding procedure (i.e. the longer the weld remains fluid, the greater is the opportunity for the hydrogen to escape). The shielding gas, regardless of composition, should therefore have the lowest possible moisture and hydrogen content.

A specific type of internal imperfections are "mechanical pores" which are caused by the entrapping of air during welding. The formation of mechanical pores is favoured by the use of high energy welding processes (high welding speed), alloys with narrow solidification ranges and small tapering angle of the weld edges. This effect can be compensated by the creation of ventilation areas achieved by a narrow air gap between the work pieces, edge preparation with taper angles of 50 - 70° and reduction of welding speed to enable proper degassing.
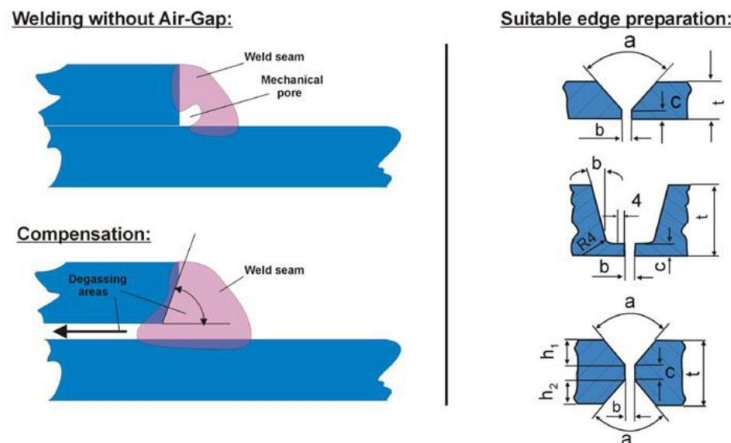
Mechanical pore formation and prevention

c) Inclusions

Oxide inclusion in aluminium welds may be avoided by a proper surface treatment prior to welding (see section 2.2). More critical are metallic inclusions. The most common is tungsten, transferred through the arc when TIG welding. Nitrogen can also be a problem because it readily forms nitrides with aluminium which reduce the mechanical properties.

d) Incomplete fusion

Incomplete fusion is perhaps the most serious of the different defects, since it significantly weakens the joint and is difficult to detect. It is the result of weld metal failing to coalesce with the base metal or with other weld metal. Incomplete fusion results mainly from incorrect welding parameters (specifically insufficient current) and insufficient edge preparation / cleaning.

e) Incomplete root fusion or penetration

Incomplete root fusion is when the weld fails to fuse one side of the joint in the root. Incomplete root penetration occurs when both sides root region of the joint are unfused.

These types of imperfections are more likely in consumable electrode processes where the weld metal is "automatically" deposited as the arc consumes the electrode wire or rod. Correct welding parameters for the material thickness should give adequate weld bead penetration. In particular a too low current level for the size of root face will lead to inadequate weld penetration. It is also essential that the correct root face size and bevel angles are used and that the joint root gap is set accurately.

The following imperfections are related to poor geometric shape of the weld:
- Excess weld metal
- Undercut
- Overlap
- Linear misalignment
- Incompletely filled groove.

Penetration and fusion are controlled by the welder, the weld joint design, the weld procedure, the welding equipment, and the shielding gas characteristics.

f) Excess weld metal (overfill)

Excess weld metal is weld metal lying outside the plane joining the weld toes. This imperfection evelops when excessive weld metal is added to the joint, ie.e too much filler metal for the travel speed used. An increase in travel speed or voltage will help to reduce cap height.
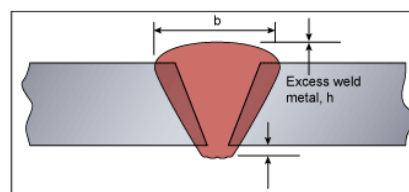

Excess weld metal

(Source: TWI)

Most standards have limit for excess weld metal which is related to material thickness, but some also have a maximum upper limits. Moreover, most specifications state that a "smooth transition is required".

g) Undercut

An undercut is an irregular groove in the parent metal. A wide spreading arc (high arc voltage) with insufficient fill (low current or high travel speed) is the usual cause.This imperfection may be avoided by reducing travel speed and/or the welding current and by maintaining the correct arc length.
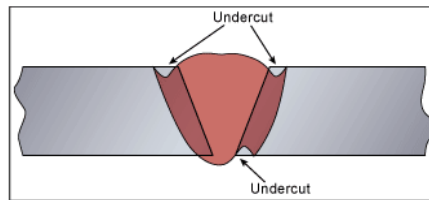
Undercut

(Source: TWI)

The figure shows undercut at surface of a completed joint but it may also be found at the toes of each pass of a multi-run weld. The latter can result in slag becoming trapped in the undercut region.

h) Overlap

Overlap is an imperfection at a toe or root of a weld caused by metal flowing onto the surface of the parent metal without fusing to it. It may occur in both fillet and butt welds.

The presence of the "overlap" imperfection is generally not allowed. It can be avoided by proper welding conditions, in particular by a reduction in weld pool size (reducing current or increasing travel speed). Adequate cleaning of the work pieces is also important.
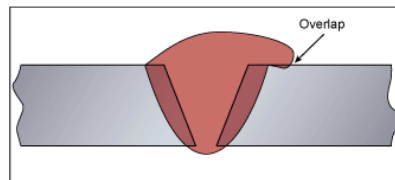

Overlap

(Source: TWI)

i) Linear misalignment

This imperfection relates to deviations from the correct position/alignment of the joint. It is primarily the result of poor component fit-up before welding. The consequence of linear misalignment can, when welding is carried out from one side, be lack of root or sidewall fusion to give a sharp continuous imperfection along the higher weld face toe.
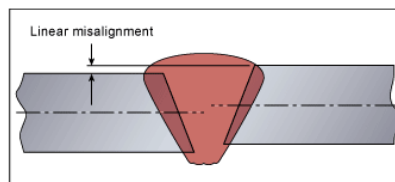

Linear misalignment

(Source: TWI)

j) Incompletely filled groove

This is a − continuous or intermittent − channel in the surface of a weld, running along its length. The joint has not been sufficiently filled due to insufficient filler metal (current or wire feed too low or too high a travel speed). The result is that the weld thickness is less than that specified in the design, which could lead to failure. Most standards will not accept this type of imperfection.
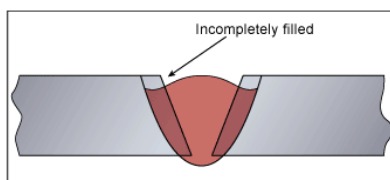
Incompletely filled groove

(Source: TWI)

There are various other types of weld imperfections which are described in the different standards and guidance documents. For details, please refer to the appropriate application codes.

k) Weld discoloration, spatter and black smut

EN AW-4xxx series filler metals produce less weld discoloration, spatter and smut than EN AW-5xxx series filler metals. Magnesium in the Al-Mg-filler metal alloys preferentially vaporizes in the arc and condenses as a black powder next to the weld bead. It has a lower vapour pressure than either silicon or aluminium. The increased vapourisation causes some disintegration of the transfering droplet as separation from the tip of the electrode occurs. Increased black smut and spatter are therefore encountered next to a weld bead made with Al-Mg filler metal alloys.

Also oxygen and moisture causes weld discoloration and smut build-up. Thus the air content in the shielding gas should be minimized.

l) Detection of welding imperfections

There are several methods of detecting weld defects in aluminium. Visual inspection is by far the easiest and most inexpensive method. Frequent visual inspection during welding can often detect imperfections early enough to allow for corrective actions before a weld is welded completed, and thus minimize repair welding at a later stage.Radiographic, penetrant, ultrasonic or eddy current are all non-destructive detection methods that are readily used on aluminium. Ultrasonic testing is the most effective and most frequently used testing method.

Method	Incomplete fusion	Pores	Cracks	Incomplete penetration	Inclusion
Radiography	X	X		X	
Penetrant			X		
Ultrsonic	X	X	X	X	X
Eddy current			X		

Non-destructive testing methods for aluminium welds

2.9 Work environment and safety

Welding operations result in fumes and spatter and thus should be properly controlled to minimise spatter and dust formation. Appropriate personal protective equipment must be used to avoid inhalation. Aluminium metal is not particularly hazardous or toxic. Aluminium oxide dust is a nuisance dust. On the other hand, aluminium dust is pyrophoric and must be suitably handled.

When welding aluminium, the emission of particulate fume and gases depends on the welding method, the applied filler metal and the type of alloy. TIG welding produces less fume than MIG welding due to the lower energy of the arc and the fact that the filler metal is not placed in the extremely hot centre of the arc. The highest amount of fume is produced by using Al – 5 % Mg filler metal.

Dust is created in the form of fumes and particles. The particles are often large in size and fall down close to the workplace, but fume particles are smaller and can travel far from the workplace. Therefore, much effort is directed towards minimising air pollution. One of the largest problems encountered when welding is the formation of ozone. MIG welding of aluminium produces more ozone than TIG welding. The amount is also dependant on welding current, arc length, welding time and type of alloy. Silicon filler metals produces the largest amount of ozone, whereas ozone production is much lower when using magnesium alloyed filler wire. In order to reduce the ozone level, proper ventilation of the workplace is therefore essential. The second possibility is the use of a shielding gas that reacts with ozone, i.e. the addition of a small amount of nitric oxide (NO) to the shielding gas. NO dissociates the ozone molecules into oxygen and nitrogen dioxide (NO_2).

2.10 Simulation of fusion welding

Fusion welding of aluminium is today well understood and can be simulated by several specific software programs (e.g. SYSWeld® or WELDSIM®).The use of the computer to simulate the joining process often allows a reduction of the development cost by reducing the amount of experimental investigations.

The welding process includes several different non-linear physical phenomena which have an influence on the final properties of the welded joint. Their consideration in a single simulation model is unrealistic:

- The mathematical description of all these acting phenomena with their respective coupling is extremely difficult.
- The computational time of such a model would be unacceptable with the available computational resources.

In order to decrease the complexity of the model, simplifications and assumptions are therefore taken into consideration depending on the focus and the respective required accuracy of the investigated problem. Over the last 30 years, research in the area of welding simulation has converged to three main domains:

- Process simulation
- Material simulation
- Structure simulation.

The process simulation deals with the welding process itself. In comparison to the structure simulation that describes the process effects on the surrounding structure, the goal of a process simulation is the description of the molten pool formation (and the fluid flow dynamics inside the weld pool) as a function of the acting physical phenomena and the resulting local temperature field. The material simulation deals with the microstructural evolution during and after the welding process in and around the weld seam on a micro- and macroscopic scale including hot and cold cracking. Many computational thermodynamic and kinetic models have been developed in the last decades to predict these phenomena. The prediction of the thermal and mechanical material properties of alloys in dependence on their chemical composition also belongs to the material simulation. The structure simulation deals with the heat effects of the welding process, which are the global temperature field and the resulting residual stresses and distortions of the welded assembly.

In industrial practice, the definition of the welding sequence and the locations where the parts should be welded provides the basis for the correct completion of the welding assembly process. Numerical simulation allows the prediction and minimization of the resulting distortions, i.e. it enables an increase of the overall product quality as well as drastic cost saving.

The welding process is simulated with the aim to control the process in a way that minimizes the stress gradient as well as tensile / compressive surface stresses. As a result, the lifetime of the assembly under dynamic loads increases and corrosion risk decrases. Virtual manufacturing helps to optimize part geometry, materials and process parameters during the early stages of a new design cycle avoiding expensive engineering changes that could occur later. It also allows user-defined weld sequencing and control of the weld manufacturing parameters such as velocity, energy input and many others.
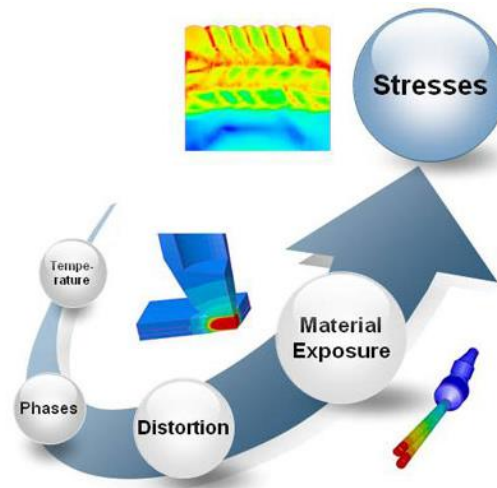
Virtual manufacturing ensures optimum weld quality

(Source: ESI)

Process modeling techniques can be also applied to optimize the functional requirements of a specific component at minimum costs. For welded aluminium structures, the load-bearing capacity of the welds is of major concern since the mechanical integrity of the welded component is generally poorer than that of the base material. As an example, the heat affected zone in Al-Mg-Si alloys represents the weakest part of the weld. Therefore, the design stress cannot exceed the minimum strength level in this zone. On the other hand, adding material thickness to increase the load-bearing capacity of the joint should be avoided because of the resulting weight and cost penalties.

The predicted weld thermal history can be used as input to a microstructure module that calculates the evolution of the particle size distribution with time. Advanced dislocation mechanics are then employed to convert the computed particle size distribution into an equivalent room temperature yield strength. The results from the microstructure module are then transferred to a mechanical module to obtain the actual residual stress and distortions.
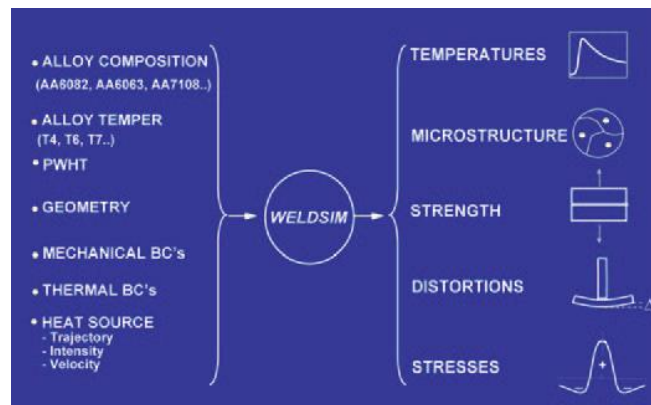
Main inputs and outputs of WELDSIM®