

# Aluminium Automotive Manual – Joining

## 3. Arc welding

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## 3.0 Introduction

Welding is a commonly used fabrication process to join metallic materials. A weld joint is accomplished by partially melting the work pieces to form a molten metal pool that solidifies and forms - after subsequent cooling - a firm, permanent connection. Sometimes, a filler metal is also added to the molten metal pool. Various fusion welding techniques are used in practice. Some general aspects which concern all the different methods are covered in section "2. Characteristics of aluminium in fusion welding". Please see this section for more details.

A most important welding method is arc welding. Arc welding is a fusion welding process which uses a power supply to initiate and maintain an electric arc between an electrode and the base material to create a molten metal pool at the welding point. Arc welding can be accomplished either with direct (DC) or alternating (AC) current. The welding region is usually protected by some type of shielding gas, vapour, or slag.

The different arc welding techniques are defined by the type of electrode:

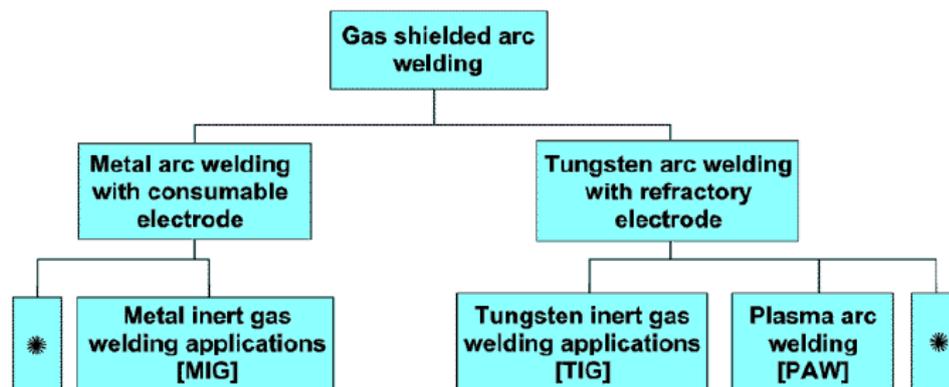
- Arc welding with a consumable electrode
- Arc welding with a non-consumable (refractory) electrode.

For aluminium materials, three arc welding processes are most relevant:

- MIG welding (often referred to as GMAW (Gas Metal Arc Welding))
- TIG welding (often referred to as GTAW (Gas Tungsten Arc Welding))
- Plasma arc welding (PAW).

The weld region is shielded from the atmosphere by an inert gas.

### Gas shielded arc welding processes with relevance to aluminium



\* further processes are known, but have no relevance to aluminium welding

Arc welding processes may be manual, semi-automatic, or fully automated. Manual welding is used for welding tasks where mechanisation/automation is not considered to be profitable. If applicable, a hand held rod may be used in TIG welding to add the filler metal to the weld pool whereas in MIG welding, the consumable electrode is always automatically fed from a reel.

In mechanised welding, the welding parameters are controlled mechanically or electronically, but can be manually adjusted during welding to ensure the required weld quality. In contrast, in automatic welding, manual adjustments of the welding parameters are not possible during welding, but may be made between welding operations. The result is a more consistent weld quality and weld bead appearance, provided that the welding parameters are properly defined. Generally a human operator prepares the materials to be welded.

For high production volumes, robotic welding is commonly used. The welding process is completely automated and robots both perform the weld and handle the parts.

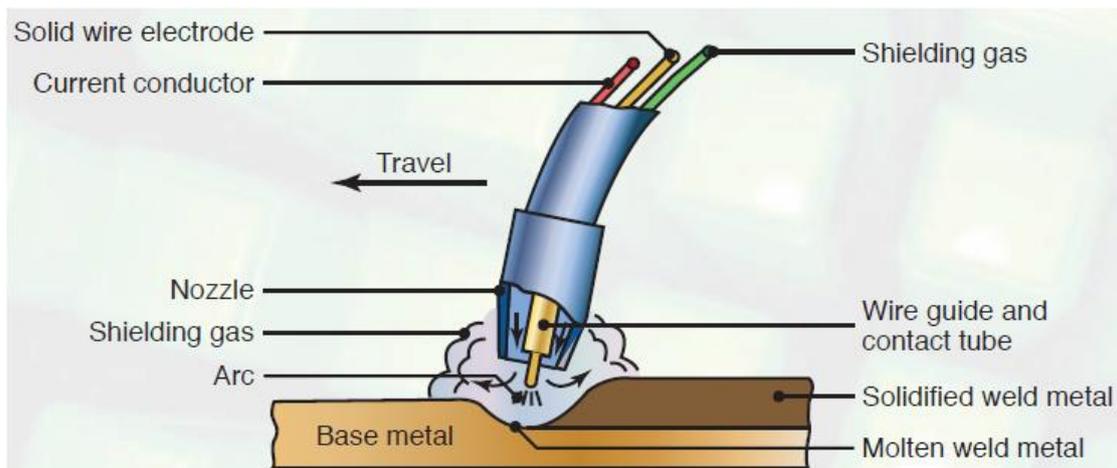
### 3.1 Arc welding with consumable electrodes

#### 3.1.1 Gas metal arc welding

Gas metal arc welding (GMAW) is a semi-automatic or automatic welding process where a continuously fed consumable wire acts as both electrode and filler material. The welding wire uncoils automatically from a reel to the welding torch. Heat is produced by an arc between the electrode and the base metal. It is a versatile welding process, suitable for practically all metals, quick and easy on thin as well as heavy gauge material and generally calls for little post weld finishing.

A differentiation can be made between metal inert gas (MIG) welding and metal active gas (MAG) welding. For steel welding, active gas mixtures (mainly argon-based gas mixtures which contain oxygen or carbon dioxide) are preferred. In contrast, for aluminium and most other metals, inert shielding gases (argon, helium or mixtures of these two) are exclusively utilized (see also section 2.5).

Although seldom used, flux cored wires can be applied as an alternative to shielding gases. In this case, evaporation of their casing in the arc creates a shielding gas environment.



**Fundamental features of the gas metal arc welding (GMAW) process**

##### 3.1.1.1 MIG welding of aluminium

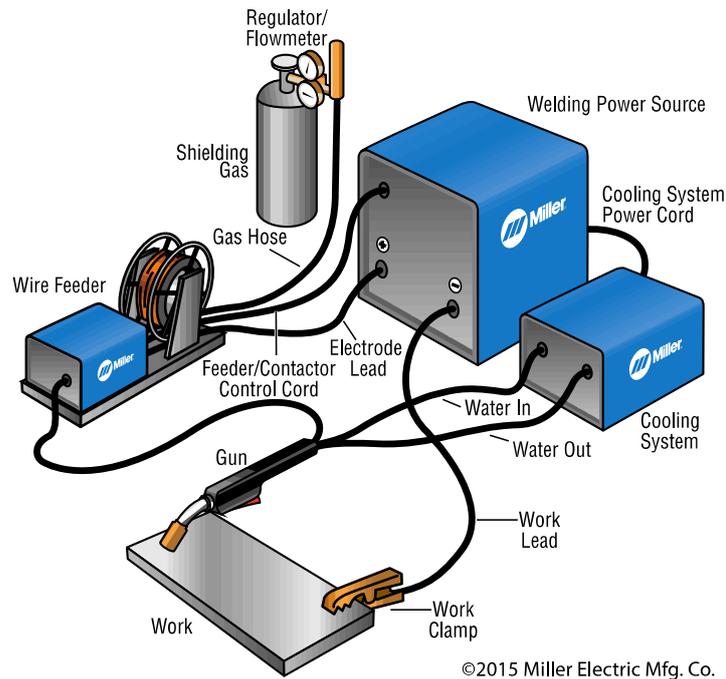
For MIG welding of aluminium, a direct current (DC) power supply with the electrode connected to the positive pole is usually used since this arrangement results in a very good removal of the aluminium oxide surface film (see section 2.1.1). The wider application of the MIG welding process with alternating current (AC) was only enabled by recent power source developments. This approach is particularly useful when welding thin aluminium materials since AC MIG welding reduces the heat input into the base material.

During the last years, significant improvements were made with respect to power source technology and weld process control. The welding current, arc length and electrode wire speed are controlled by the welding machine and set by the operator. The MIG process uses a continuous wire feed and, for the majority of welding operations, it is important that the rate at which the wire burns off in the arc is matched by the wire feed speed. Otherwise, an unstable arc and variable weld quality may result. In general, the feeder is of the push-pull type, i.e. the wire is pushed through a feed pipe and at the same time drawn by the gun. Wire feeding is provided either by an integrated wire drive inside the power source housing or an external wire-feed unit.

Conventional stepped power sources use a transformer to produce the desired welding voltage. A rectifier, positioned downstream from the transformer, generates the rectified

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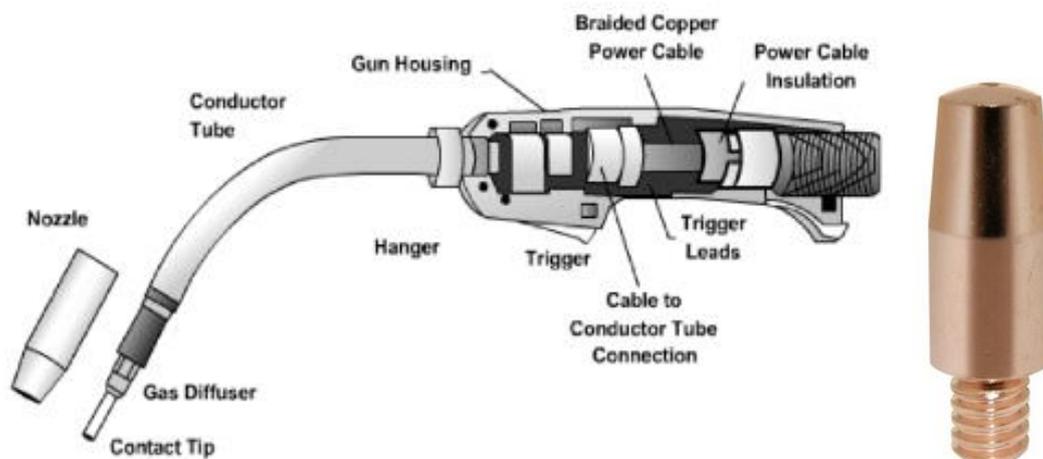
welding current from the supplied alternate current. An adjustable induction coil smooths out unwanted current peaks, thereby reducing the tendency to produce welding spatter.



### Schematic of the MIG welding process

(Source: Miller Electric Mfg. Co.)

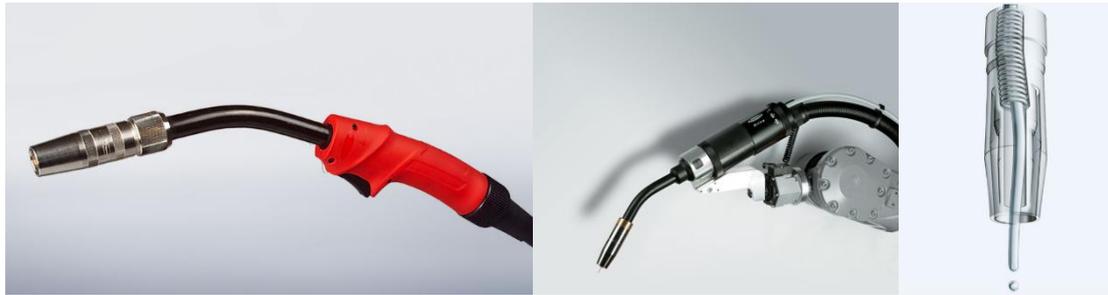
The welding current flows from the power source through the gun cable and welding torch (or welding gun) to the wire and across the arc. On the other side of the arc, the current flows through the base metal to the work cable and back to the power source. The filler wire is fed via two or four drive rollers into the welding torch, where the current is transferred either via a contact tube or a contact tip.



### Schematic of a MIG welding gun (left) with current transfer at the tip (right)

(Source: Lincoln Electric Company)

The shielding gas flows through the gun and out the nozzle. The free wire end is concentrically surrounded by the gas nozzle. The shielding gas prevents chemical reactions between the hot work piece surface and the surrounding air and protects the weld pool from contamination. In addition to controlling the arc behaviour and deposition rate, the shielding gas is also partly responsible for the material transfer and the shape of the resulting weld seam.



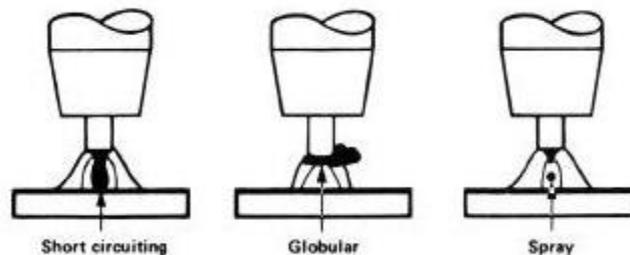
**Gas-cooled welding torches for manual (left) and robotic welding (center) with current transfer using a contact tube (right)**

**(Source: Fronius)**

Manual and machine welding torches are available in gas-cooled and water-cooled versions. Gas-cooled welding torches are cooled by the shielding gas, while water-cooled welding torches offer more effective cooling. For welding currents of 300 A and above, water-cooled welding torches are standard.

In the standard DC MIG welding process, most of the heat developed in the arc is generated at the electrode (positive pole). The result is a high wire burn-off rate and an efficient heat transfer into the weld pool. The selection of wire diameter and wire feed speed determine the welding current as the burn-off rate of the wire will form an equilibrium with the feed speed.

The manner in which the filler metal transfers from the electrode to the weld pool largely determines the operating features of the process. There are three basic metal transfer modes in gas arc welding: short-circuiting, globular, and spray:



**Types of metal transfer**

In short-circuit (or dip) transfer welding, metal transfer occurs when an electrical short circuit is established. At low welding currents, the tip of the continuously fed wire may not melt sufficiently fast to maintain the arc, but can dip into the weld pool. An electrical short is created and the current spikes. The combination of surface tension forces and the magnetic pinch force created by the current spike cause the droplet to transfer to the weld pool and the arc is re-established. The cycle is repeated about 100 times per second.

Due to the low heat input, this metal transfer mode would be particularly useful for joining thin materials. However, the violent nature of the short-circuiting event results in relatively high spatter levels and the process has a tendency to generate incomplete fusion discontinuities when welding thicker materials. Thus for a long time, the short-circuit transfer process variant was not used for aluminium welding.

Only recently, new equipment developments enabled significant improvements in the control and stability of short-circuiting metal transfer. Several manufacturers now offer advanced versions of the MIG welding process for thin sheet and/or positional welding based on the short-circuit transfer mode (see section 3.1.1.6).

As welding current and voltage are increased, metal transfer takes on a different appearance. In the globular transfer mode, a molten metal ball builds up at the end of the electrode with a diameter which is usually greater than the wire itself. When the drop finally detaches either by gravity or short-circuiting, it falls onto the work piece producing high heat, an uneven weld surface and spatter. Due to its erratic nature, the globular transfer mode is not used for aluminium welding.

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By raising the welding current and voltage still further, metal transfer changes from larger globules through small droplets eventually to a vaporised stream. In the spray transfer mode, small molten drops are detached from the tip of the wire and projected by electromagnetic forces towards the weld pool. The wire does not make contact with the weld pool, i.e. the arc is stable and little spatter is produced. On the other hand, the continuous spray of small molten droplets enables high deposition rates and deep penetration into the parent metal. The low melting point of aluminium and its alloys allows the application of the spray transfer mode even at relatively low currents. Thus for a long time, spray metal transfer was the preferred technique for aluminium welding.

A drawback of the spray arc welding method is its high thermal input, which means that it is best suited for welding thicker materials and for welding in flat and horizontal positions. When welding thinner aluminium components, the risk of burn-through and warping issues calls for careful control of the processing parameters. As a possible solution, the fine wire MIG welding process (with wire diameters < 1 mm) was considered. However, the soft, fine aluminium wires are difficult to feed and this approach proved to be not very successful.

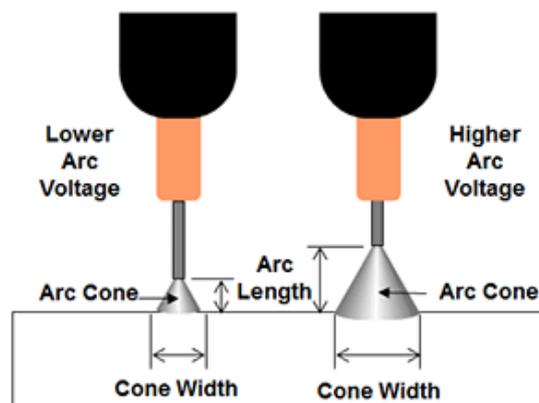
Today, the pulsed spray method (see section 3.1.1.2), a variant of the spray transfer mode where metal transfer is achieved by applying direct current pulses, is normally applied, in particular for thinner aluminium work pieces.



**Manual and automated MIG welding of an aluminium car body structure**

**(Source: Ferrari)**

In MIG welding, the electric arc is dynamic, i.e. current and voltage are constantly changing. Current effects the consumption rate of the electrode, i.e. the higher the current level, the faster the electrode melts. Voltage controls the length of the welding arc and the resulting width and volume of the arc cone. As voltage increases, the arc length gets longer (and arc cone broader).



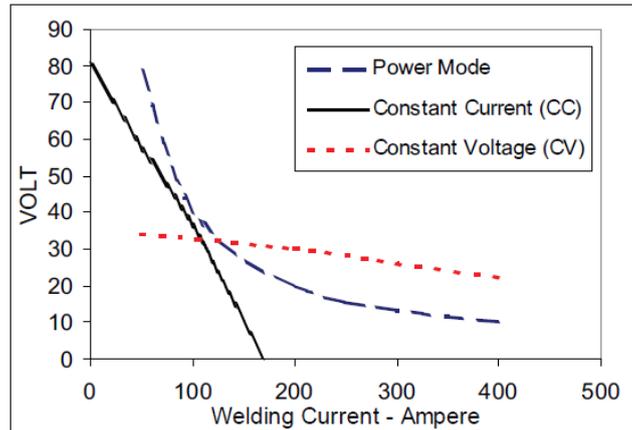
**Effect of Arc Voltage**

**(Source: Lincoln Electric Company)**

Many MIG welding power sources are designed with a constant voltage characteristic. This is most important in manual welding where a fixed arc length cannot be maintained during welding. When a constant voltage power source is used, a small increase in the arc length increases the arc voltage and therefore results in a large drop in arc current. Consequently the wire burn-off rate decreases, the tip of the wire moves back closer to the weld pool, decreasing the voltage and raising the current again. The result is a “self-adjusting arc” where arc length and filler metal deposition rate are maintained constant almost irrespective of the

torch movement, although weld penetration is not maintained constant because the current is varying. On the other hand, a constant current power source has also advantages. In this case, a large change in arc voltage results in only a small change in arc current. Heat input is reasonably constant, leading to more consistent weld penetration.

Just as it is possible to perform MIG welding using constant current or constant voltage power supplies, it is also possible to perform MIG welding using power supplies where the overall arc power is regulated. In the Power Mode™ process variant, the wire feeding speed and the overall arc power are preset. The arc length is set by changing the arc power, i.e. increasing arc power increases the arc length.



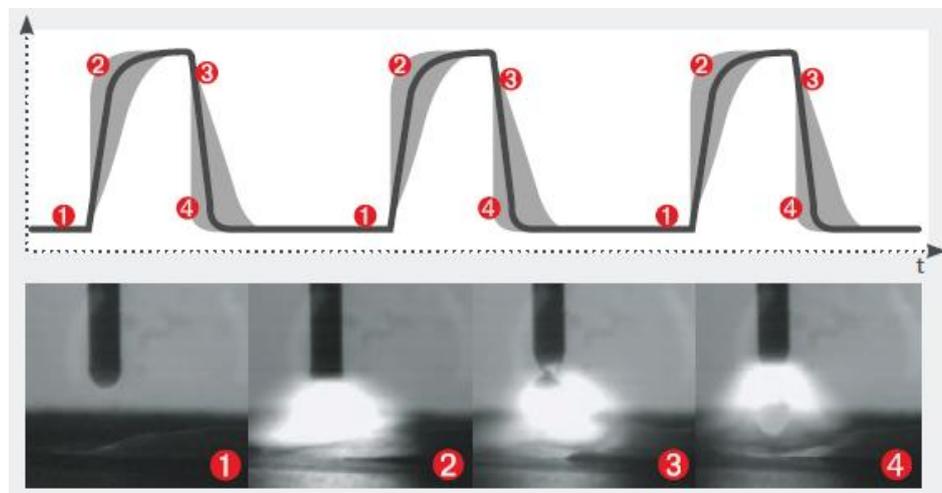
**Comparison of the constant current, constant voltage and constant power slopes**

(Source: Lincoln Electric Company)

The power supply responds to changes in voltage sensed at the welding arc. However, unlike a constant voltage weld process, the Power Mode™ will respond with less current change. The benefit of this type of control is most obvious in applications where energy and penetration must be closely monitored and consistent, i.e. it aids in the control of the arc's response to variations in stick-out. Spatter levels are usually lower than those obtained from constant voltage power supplies.

### 3.1.1.2 Pulsed MIG welding

Pulsed MIG welding is a further development of the standard MIG welding process. It was developed in the early 1960s, but wider adoption on the shop floor started only in the late 1970s. With the introduction of solid state electronics, pulsed arc welding became the standard MIG welding technique for aluminium.



**Pulsed MIG arc welding features a controlled, short-circuit-free material transfer**

(Source: Fronius)

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Characteristic of the pulsed arc technique is the controlled material transfer. Pulsed MIG welding maintains an arc at low current and superimposes short periodic pulses (30 – 300 Hz) of high current in order to detach and transfer single drops of molten metal from the electrode to the weld pool. In the background current phase, the energy supply is reduced to such an extent that the arc is only just stable and the surface of the work piece is preheated.

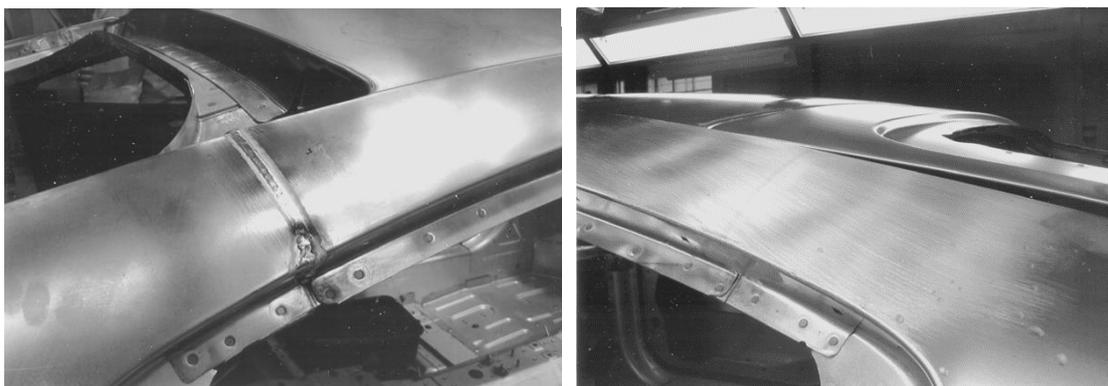
The peak current phase is used for targeted droplet detachment. A precisely controlled current pulse supplies the heat to melt the filler wire, but also to pinch off just one molten droplet for each pulse. The droplet size is adjustable. Although the metal transfer occurs at the high current levels necessary for spray transfer, the average current is reduced. The reduction of the overall heat input decreases the size of the weld pool and heat-affected zone. Furthermore, a thicker electrode can be used when welding thin material, i.e. the deposition rate (welding speed) can be increased.



**Robotic MIG welding with through-arm (left) and external wire feeding (right)**

**(Source: Lincoln Electric Company)**

With the pulsed arc technique, an unwanted short circuit with simultaneous droplet explosion is ruled out as is uncontrolled welding spatter. There is less deformation of the work piece and less need for post-weld finishing. The smaller weld pool offers greater versatility, making it possible to weld in all positions. It also helps to bridge gaps when fit-up is less than optimal. Furthermore it provides the operator with excellent directional control over the weld pool, which improves bead appearance.



**Robotically applied MIG weld joining the C pillar to a roof section on the Jaguar XK**

**(Source: Jaguar)**

Pulsed MIG welding requires a power source which can supply the two different current levels. Modern microprocessor-controlled power sources allow to fine-tune arc conditions e.g. for material thickness, wire diameter or material type and have a built-in set of programs that automatically select the optimal welding parameters enabling perfect and reproducible results. Therefore practical application is much easier compared to older power source types where all pulse parameters had to be adjusted by the operator.



**Microprocessor-controlled power source for short circuit, spray and pulse-spray metal transfer and a push-pull wirefeeder (left)**

**(Source: The Lincoln Electric Company)**

### 3.1.1.3 Advanced control techniques for pulsed MIG welding

Further advancements of the MIG welding process were enabled in recent years by the increasing use of microelectronics and digital technology. The results are even lighter power sources, faster controlled arc movements and improvements in the ignition process. The latest developments are completely digitalized welding systems. The crucial difference compared to conventional computer-controlled power sources is the incorporation of a digital signal processor which carries out the welding process control. The new developments provide an even easier user guidance and further improved welding characteristics.

In pulsed MIG welding, the output of the power source is neither constant current nor constant voltage. Modern power sources rather monitor and change both voltage and current at extremely fast rates in order to maintain stable arc welding conditions. The continuously adjustable output current is constantly measured and kept within the ideal range. Also the pulse waveform is continuously adjusted by providing a fast or slow front edge on the pulse to transfer the droplet at the proper rate. The back edge falls at a controlled rate to add the required heat to wet the droplet to the molten metal pool.

Some specific control features that significantly improve pulsed MIG welding performance are described in the following. As an example, pulsed waveforms have been developed that use true constant current. The purpose of these waveforms is to eliminate the rapid variations of the arc length (“hunting”) that is common when using 5XXX filler metals. This approach has been reported to be successful, with a more stable arc and no arc hunting.

Another example is the Profile Pulse™ feature that significantly improves the weld bead appearance. It creates a TIG-like weld bead profile without having to weave or step the torch.



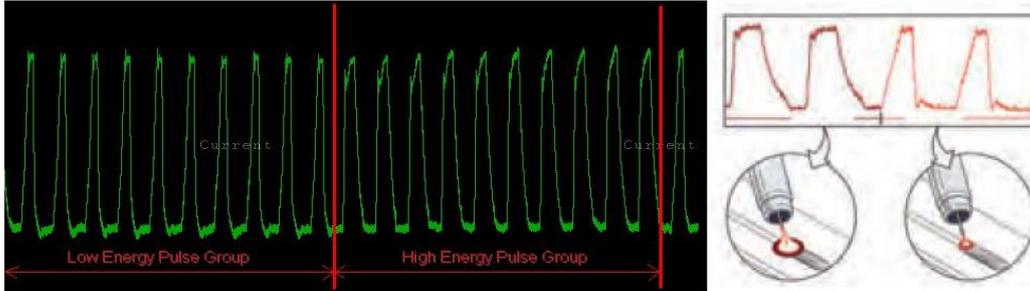
**Typical consistently spaced ripple pattern of a MIG Profile Pulse™ weld**

**(Source: Miller Electric Mfg. Co)**

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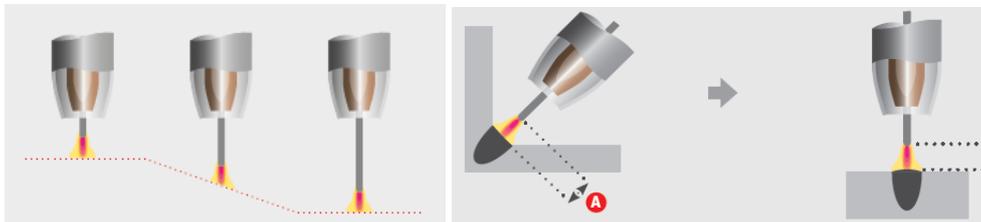
The wire feed speed and arc power are modulated at a low frequency, thus producing a consistently spaced ripple pattern. The spacing of the ripple pattern can be changed by changing the switching frequency (usually from 0 to 5 Hz). Commonly used for highly visible welds, the Profile Pulse™ program can also aid in out-of-position welding.

The same effect can be achieved without changing the wire feeding speed e.g. by superimposing a low frequency pulse over the normal pulse and adjusting the relative length of the high-current phase per cycle ("SynchroPulse" function) or the Pulse-On-Pulse™ process which uses a sequence of varying pulse wave shapes. In the Pulse-On-Pulse™ process, a number of high energy pulsed is followed by the same number of low energy pulses. The high energy pulses provide a hotter arc (longer arc duration) while the low energy pulses allow the weld pool to cool. As a result, heat input can be controlled even more precisely.



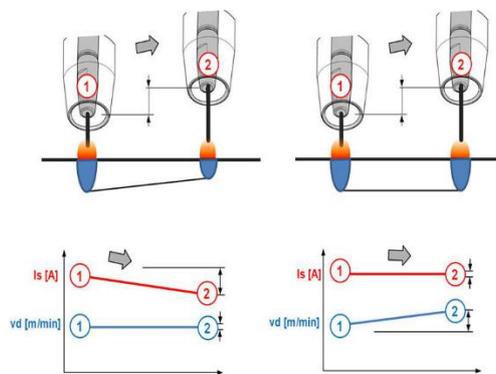
**Pulse-On-Pulse™ process**  
(Source: Lincoln Electric Company)

The high measuring and control speed of modern power sources also offer functions such as the penetration stabiliser and the arc length stabiliser feature. Arc-length control ensures that the arc length remains constant at all times, even when the stick-out changes. It maintains a consistently short arc, which allows to achieve higher welding speeds.



**Constant arc length despite varying stick-out (left) and changing torch position (right)**  
(Source: Fronius)

Weld penetration can be kept constant by using current controls to adjust the heat so that changes in electrode extension do not affect heat input. Another possibility is to make use of an active wire control to compensate for the influence of the torch stand-off distance on the welding result.



**The activated penetration stabiliser controls the wire feed speed instead of the welding current (left) and ensures constant weld penetration (right)**

(Source: Fronius)

Significant improvements have been achieved also with regard to the start and stop phase. The ideal ignition sequence can be optimised and programmed with the ignition parameters precisely matched to the diameter and quality of the wire. A special ignition variant takes into account the good thermal conductivity of aluminium. In order to prevent fusion defects in the start-up phase, the base metal has to be melted right away. Thus, ignition is effected at considerably higher power. Once there has been sufficient heat input into the weld pool, the welding power is decreased. Furthermore, the ignition energy can be adapted to the actual wire temperature at the instant of arc initiation. The result is a quiet, jerk-free arc ignition.

Towards the end of the seam, there is a danger of the weld pool collapsing or dropping through as a result of the heat running ahead in the work piece. This is counteracted by reducing the welding power to an even lower value for filling the crater. At the end, a controlled current pulse sheds the last molten droplet, preventing a solid globule from forming at the tip of the electrode.



**End of welding without burn-back pulse (left) and with burn-back pulse (right)**

**(Source: Fronius)**

### **3.1.1.4 High performance MIG welding**

There is only limited scope for translating higher arc power into higher welding speeds. When the power is increased, the arc pressure rises very rapidly, which makes the weld pool difficult to control. The result may be an irregular bead shape, porosity or excess penetration.

Nevertheless, there is an increasing demand for high quality MIG welding processes with increased productivity. By definition, high-performance MIG welding processes have one or more solid wires of 1.0 mm or 1.2 mm diameter with a wire feed speed of more than 15 m/min. Processes with a greater wire cross section may also count among the high-performance welding processes. The enhanced deposition rate can be used either for welding larger cross-sections (i.e. improved gap bridging) or for increased welding speeds.

The applied power source technology (as well as the wire feeding system and the welding torches) corresponds to that used in standard MIG applications, but in design and performance, the components are specifically adapted to the requirements of high-performance welding.

#### **a) Large wire MIG welding**

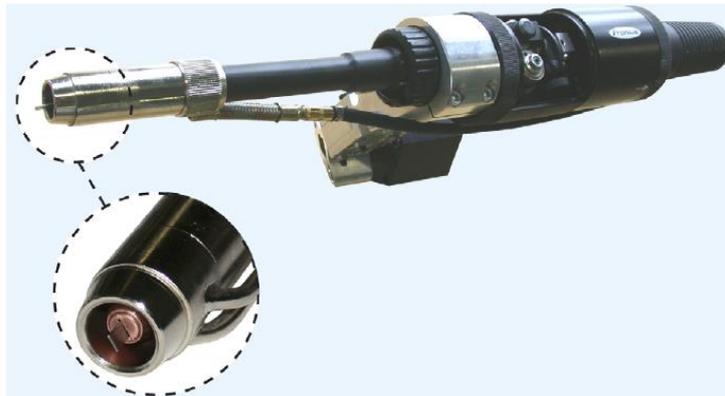
In principle, an enhanced deposition rate can be achieved by a longer free wire tip in the welding torch (greater “stick-out”) and an increase of the wire feeding speed. However, particularly with aluminium, there is an upper limit for the wire feeding speed; the limiting values are approximately 18 m/min with 1.2 mm and around 11 m/min for 1.6 mm diameter wire.

The better option is the use of wires with a higher cross-sectional area. With round wires of up to 3.2 mm diameter, a maximum deposition rate of 5 kg/h could be achieved. However, the main disadvantage of larger wires is also the wire feeding process; the soft aluminium wires are difficult to feed as they lack column strength. Thus for aluminium, practical application of large wire welding is very limited.

### b) Flat wire MIG welding

A more promising alternative is the use of a flat wire. When a flat strip wire is deflected by its wider side, it can be fed better than a round wire with the same cross-sectional area. The rectangular cross section of the wire also allows the transport of more current with less resistance due to the skin effect (current is best conducted around the outside of the welding wire).

The arc burns stable on the whole edge of the strip wire. At the strip wire, the arc has a pronounced elliptic shape, but becomes almost round at the welding site. Different welding results will be obtained, depending on whether the strip-wire is fed parallel or at right angles to the direction of welding. The wider arc leads to a lower arc pressure, resulting in decreased penetration and improved gap bridging. The maximum deposition rate reaches 4 kg/h for aluminium. MIG welding with a flat wire basically takes place under the same process conditions as those applicable to round wire.

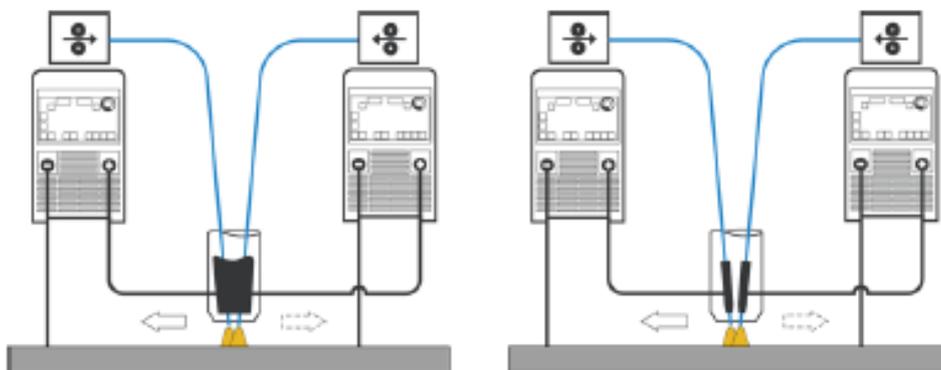


Push-pull strip-wire MIG torch with water-cooled gas nozzle  
(Source: Fronius)

### c) Twin wire MIG welding

A greater increase in deposition rate is offered by the application of a two-wire technology. Basically, two variants are possible:

- In **twin wire welding**, both wire electrodes are guided jointly through the same contact tube which means that both electrodes have same electrical potential on a continuous basis.
- In **tandem welding**, each electrode has a separate contact tube. The contact tubes are electrically insulated from each other, i.e. it is possible that the two electrodes have different electrical potentials.



Twin wire welding with a common contact tube (left) and tandem welding (right)  
(Source: Fronius)

After initial successes with simultaneous melt-off from two wire electrodes in MAG welding of steel, efforts were made to transfer these results to aluminium MIG welding. However, the respective trials did not deliver the expected gain in welding speed. The small arc length repeatedly led to a short circuit between one wire electrode and the weld pool, which then caused arc extinction on the second wire electrode. Consequently, the high current density on the first wire electrode quickly broke the short circuit.

The result was an instability of both arcs owing to the wide fluctuations in arc length and a large amount of weld spatter. Although both the spattering and the instability could be reduced when the arc length was increased, the corrective measures also decreased the welding speed. Consequently, further development of the twin wire concept was discontinued.

The definitive solution for an increased deposition rate based on the two wire method proved to be the tandem MIG welding process where the two wires can be operated independently (see section 3.1.1.5).

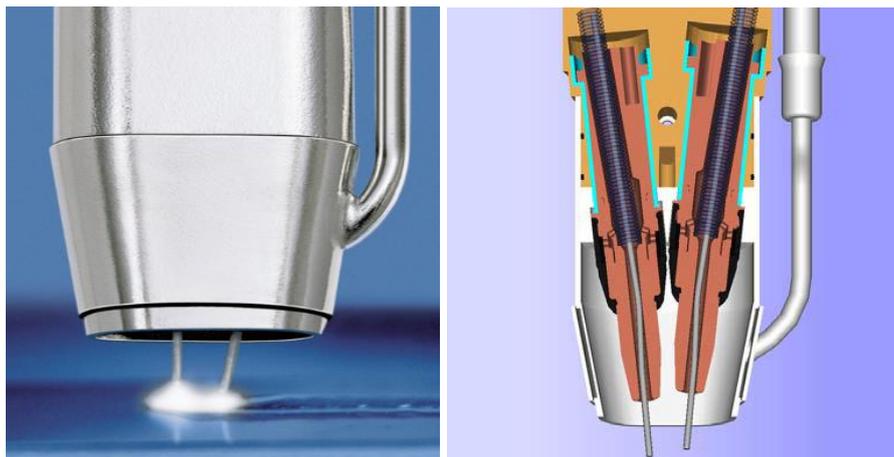
### d) Hybrid MIG welding

For even higher performance, the MIG welding process can be combined with other welding techniques. Relevant for practical application are the Laser MIG welding process (see section 10.3.1) and the Plasma MIG welding process (see section 10.3.2). In hybrid welding, both techniques act in the welding zone at the same time and influence each other. The results are beneficial synergy effects such as highest possible speed with the highest possible quality, process stability and spatter-free welding even at maximum speed, improved gap bridging and less geometrical distortion.

### 3.1.1.5 Tandem MIG welding

Tandem MIG welding systems comprise two wire feed units and power sources. Both wires - which are electrically isolated from each other - are continuously fed through a special welding torch and melt simultaneously in a common weld pool. Each wire is separately contacted, i.e. they can be operated independently with different wire diameters, current levels or operating modes.

Welding commonly takes place with the two wires in-line along the joint. However, the wires may be positioned also side by side or at any angle in between allowing precise control of bead width and gap filling.



**Tandem MIG welding process (left) and torch cutaway (right)**

**(Source: Fronius)**

Tandem MIG welding requires a special power source control that enables the stable operation of two independent welding arcs working in close proximity. The length of the two electric arcs is separately controlled which means that it is possible to ensure a stable arc and perfect drop release in both cases and thus achieve low spatter. Since the length of each of the two arcs can be kept short, the weld pool remains narrow. But the longer weld pool

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produced by the consecutively placed arcs enables a significant increase of the welding speed.

The first electrode in-line is referred to as the lead electrode and the second electrode is the trail electrode. The function of the lead wire is to ensure that the base metal is thoroughly melted, i.e. to generate the majority of weld penetration and metal deposition. The trail wire controls the weld pool for bead contour and edge wetting; it also adds to the overall weld metal deposition rate. Furthermore, the trailing arc prolongs the weld-pool degasification time, i.e. it reduces pore-formation sensitivity.

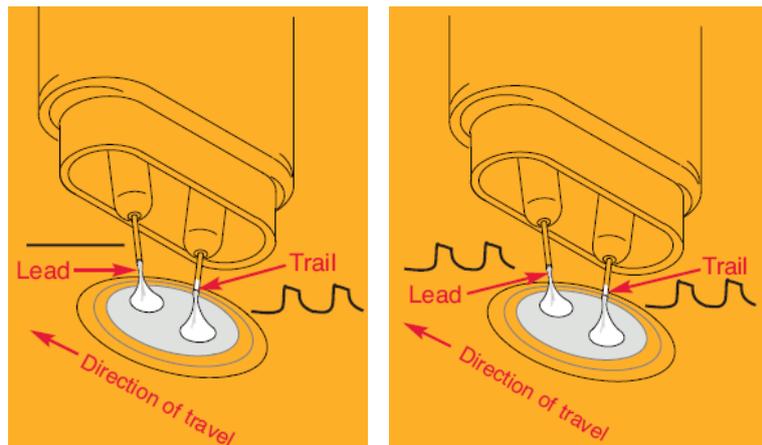
The process would work with a large diameter lead wire and a small diameter trail wire (which therefore draws less current) using the same voltage for both electrodes. However, the lead and trail welding wires are generally specified to be the same diameter to satisfy inventory constraints and/or because the direction of welding must be reversed. Consequently, a slightly higher power is normally set for the leading arc.

The electrical insulation of the two electrodes allows the independent selection of the arc type (constant DC arc or pulsed arc). Thus there are four basic operating modes for tandem MIG welding:

- Pulsed arc in both electrodes
- Constant voltage mode (“standard arc”) in the leading electrode / pulsed arc in the trailing electrode
- Pulsed arc in the leading electrode / standard arc in the trailing electrode
- Standard arc in both electrodes.

The first two operating modes are mainly used in practice as they address two critical demands: high speed thin metal welding and heavy gauge material welding. The “pulsed arc in the leading electrode / standard arc in the trailing electrode” mode has less relevance, but may be applied to achieve maximum welding speed and gap bridging. The “standard arc in both electrodes” mode is seldom used.

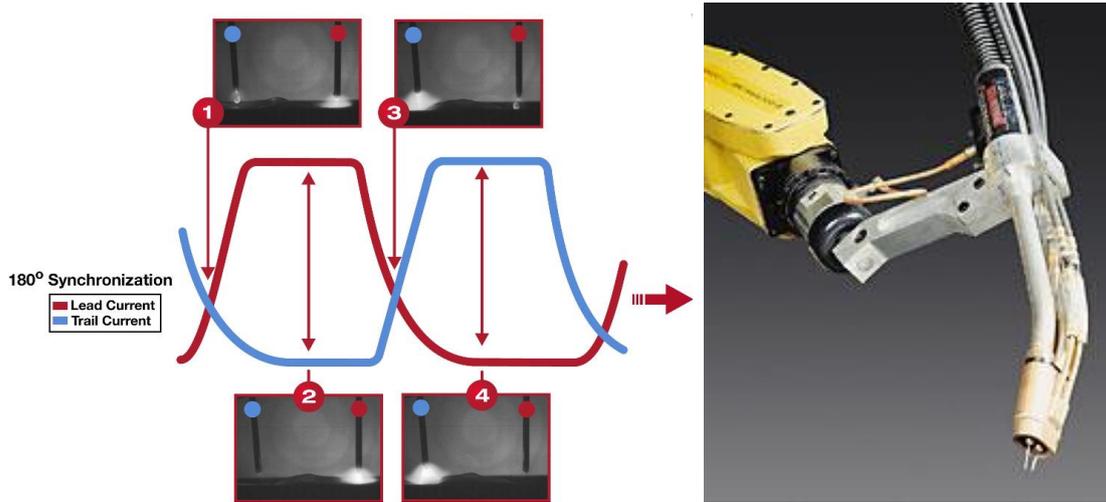
DC welding with a combination of a constant positive voltage in the leading electrode and a positive pulse in the trailing electrode is ideal for deep penetration. The lead electrode ensures a high deposition rate whereas the pulsed trail arc cools the molten metal pool and minimises electromagnetic arc interference. The independent control of the lead and trail arc parameters offers a wide operating range and allows to achieve an optimum balance between weld penetration and fill.



**Main operating modes in tandem MIG welding**

**(Source: Lincoln Electric Company)**

The “pulsed arc in both electrodes” configuration is used for optimally controlled metal transfer and to manage total process heat input on thin gauge material and other heat sensitive applications. The current in each wire is alternately pulsed to avoid magnetic interactions between the two arcs, leading to increased stability, minimal arc blow and reduced spatter. This requirement imposes strict operation constraints and the process must be carefully applied.



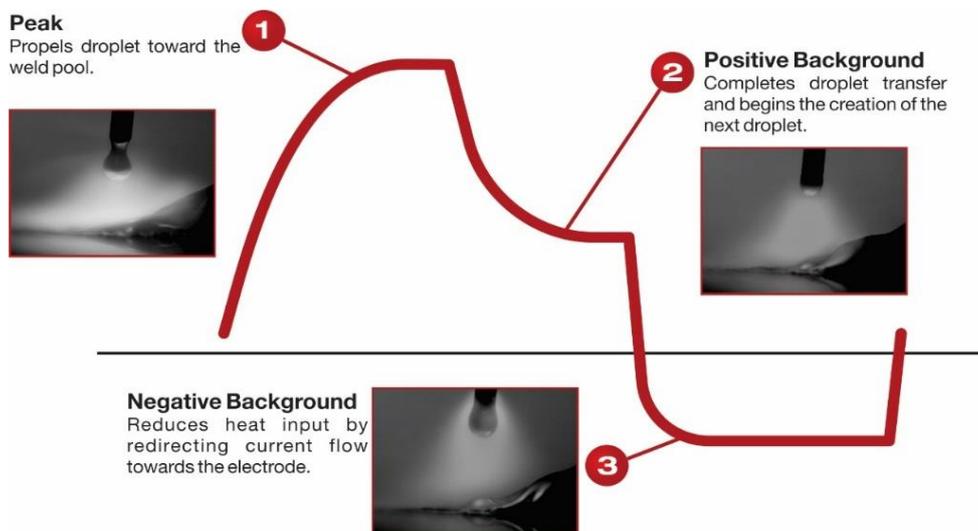
**Tandem MIG welding with 180° phase-displaced pulsed arcs for optimum metal transfer**  
 (Source: Lincoln Electric Company)

The ability to distribute the total welding current across two separate welding wires provides unique benefits for high-speed welding. On thin gauge materials, speed-limiting quality issues are either burn-through or insufficient gap filling characteristics. The tandem MIG welding process addresses both of these issues. It allows the lead wire to generate the required penetration while the trail wire creates added fill. Also, the trail arc acts as an additional force that pushes the molten metal for better follow and wetting capabilities.

Tandem MIG welding is typically used for mechanised or robotic welding in order to keep torch position precisely enough in relation to the weld seam. Wire movement is separately controlled for each arc, a synchronisation unit on the power sources ensures appropriate material transfer.

**3.1.1.6 Pulsed MIG welding with alternating current**

MIG welding with alternating current (AC) has existed for over 20 years, but has only been used in few applications. The limiting factor was the availability of a suitable power supply. A resurgence of AC MIG welding was only possible in the last few years when modern inverter, software-controlled power supplies enabled much better process control.

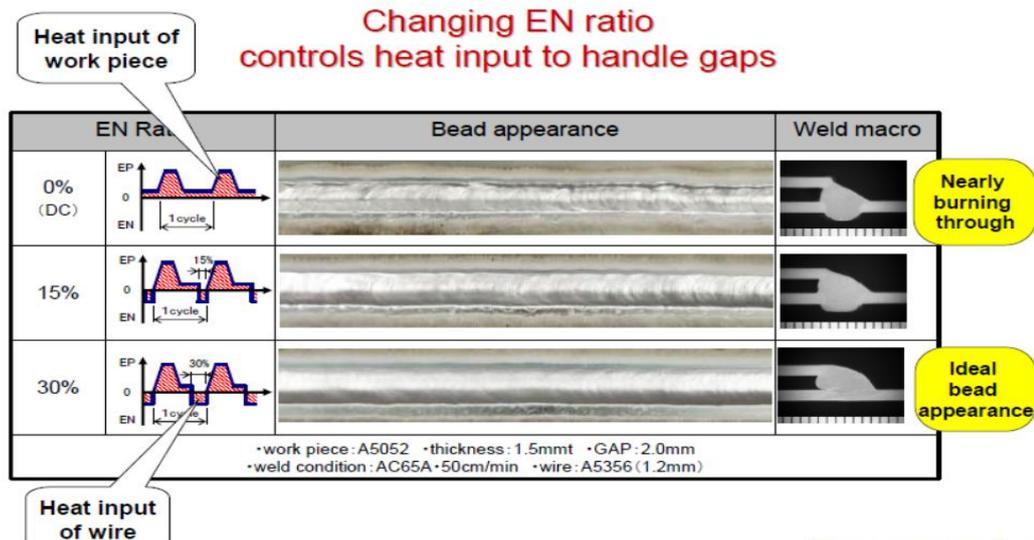


**Schematic of AC Pulse Waveform in AC GMAW**  
 (Source: Lincoln Electric Company)

In the AC pulsed mode, both negative and positive polarity pulses are applied to the wire electrode. In the electrode positive (EP) mode, heat input into the work piece is high (i.e. high

## THE ALUMINIUM AUTOMOTIVE MANUAL

weld penetration), along with cathodic arc cleaning. On negative polarity (EN), the heat input is lower, but the wire burn-off rate is greater. The overall lower heat input reduces geometrical distortion, allows thinner materials to be welded and larger gaps to be bridged without burn-through. In conjunction with pulse control and specific pulse adjustments, a significant improvement of the arc stability can be achieved and spatter can be reduced.



**AC pulsed MIG welding allows control of heat input and the ability to bridge gaps**

**(Source: Miller Welding Automation)**

Thus it is possible to optimally control the deposition rate, the formation of the weld and the bonding conditions between base material and filler metal. The applied AC frequencies vary over a range of approximately 50 – 400 Hz and the arc is usually running in the range of 10% EN/90% EP to 30% EN/70% EP. In most cases, the AC pulsed wave looks very similar to a conventional DC pulsed wave with a shorter EN pulse added at the end. Compared to DC pulsed MIG welding, the produced weld seams are of the same height and width, but since the heat input at the same wire feeding speed is lower, there is less “melt-through” or “read-through”. The welds have low notches at the edge of the seam and a uniform weld scaling; there are no visual surface imperfections.

In response to the growing demand for heat-reduced arc welding processes, some manufacturers offer dedicated AC MIG welding power supplies. Other manufacturers manufacture a separate AC module that can be added to a current generation power supply at any time.



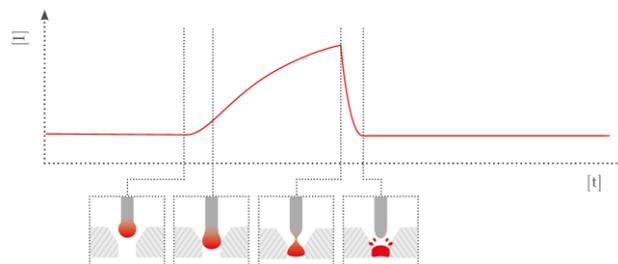
**Conventional DC Inverter supply with an AC advanced module underneath**

**(Source: Lincoln Electric Company)**

### 3.1.1.7 Advanced MIG welding techniques using short-circuit (“dip”) metal transfer

MIG welding using the short-circuit (or dip) metal transfer mode produces the lowest heat input, making this process variant particularly attractive for thin sheet applications where precise control of the weld pool is required. Thanks to advanced process control methods, properly controlled short-circuit transfer MIG welding can produce joints with a quality comparable to that of the TIG (GTAW) welding process, at production rates characteristic of the MIG welding process. The ability to generate welds with low and controlled heat input also enables successful welding of crack-sensitive materials.

In short-circuit metal transfer welding, the molten tip of the electrode contacts the weld pool and induces an electrical short. The resulting current spike increases the strength of the electromagnetic field surrounding the wire and creates a force which separates the molten part from the rest of the electrode (“pinch effect”). Surface tension forces draw the molten metal into the weld pool and the cycle begins again. The main difficulty associated with this type of metal transfer is the high spatter level. In order to balance maintaining a molten wire tip (for metal transfer) against an excessive current/pinch force (causing spatter), the most critical factor is the rate of current rise during the droplet detachment phase.



**Short-circuit metal transfer causes high spatter levels**

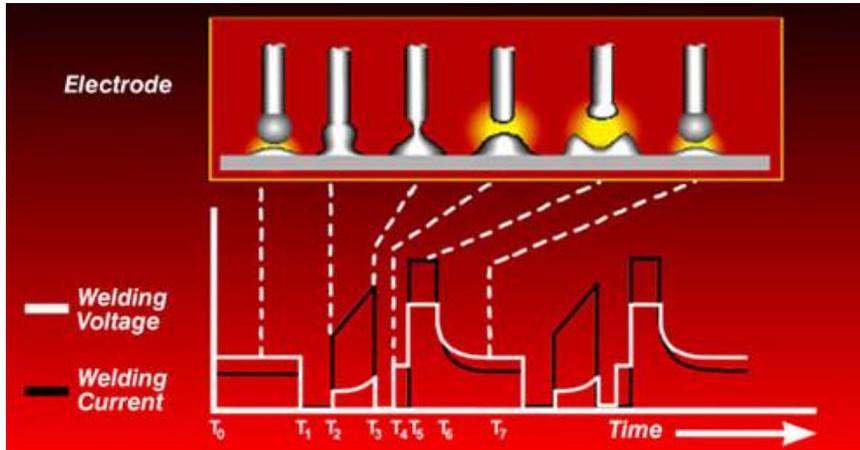
**(Source: Fronius)**

Advanced versions for a heat-reduced MIG welding process based on short-circuit metal transfer control the current profile throughout the various stages of the metal transfer cycle or use the reciprocating wire feed approach (see section 3.1.1.8). Further process variants synchronize both current and wire feed control during and/or before the short-circuit stage.

There have been numerous attempts to improve the arc behaviour during short-circuit metal transfer by closer control of the applied current cycle, especially in the re-ignition phase after the short circuit. As early as the 1980s, first trials were made to reduce the current immediately before the short circuit bridge breaks, followed by a high voltage pulse to ease arc re-ignition. Newer attempts introduced a closely controlled current increase to facilitate the separation of the molten metal ball in the short circuit phase, immediately followed by a rapid reduction of the welding current prior to the facilitated arc re-ignition. Since the current in the wire is reduced towards the end of the short circuit phase, the overall heat input is reduced and the weld pool is colder and less fluid.

The successful application of this control concept was made possible by the recent development of digitally controlled power sources. Welding equipment suppliers have come up with a number of solutions (e.g. EWM ColdArc®, Fronius Low Spatter control (LSC), Lincoln Electric Surface Tension Transfer (STT), Miller Regulated Metal Deposition (RMD™), etc.) which are characterized by slightly different current profile characteristics. The welding process is regulated by continuous measurement and evaluation of the arc voltage. The power source instantaneously reacts to all phases of the weld metal transfer in accordance with the real situation of arc.

The proper control of the current waveform throughout the various stages of the metal transfer cycle enables smoother droplet transfer, precise bead placement, and reduced spatter levels. Since the advanced short-circuit metal transfer modes are insensitive to changes in the contact tip-to-work piece distance, they are ideally suited for automatic or semi-automatic operation.



**Welding voltage and current in the individual metal transfer phases of the Lincoln Electric Surface Tension Transfer (STT) process**

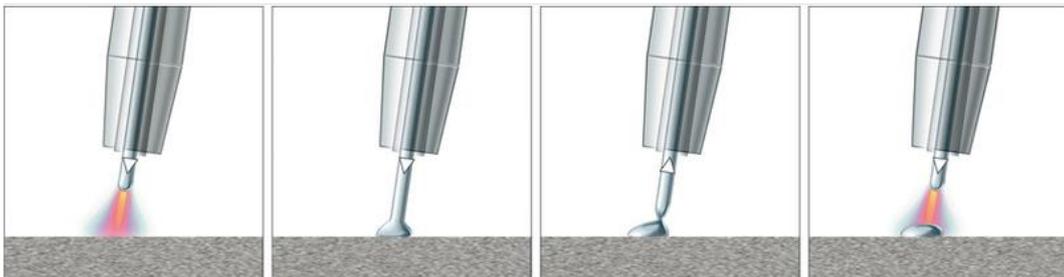
(Source: The Lincoln Electric Company)

In a first phase (which corresponds to the conventional short-circuit metal transfer process), the electric arc is burning between the end of electrode and the weld pool and a ball of molten material forms at the end of the electrode. When the size of the molten metal ball reaches the pre-determined size and contacts the weld pool, the welding current is rapidly reduced to a minimum to avoid any spatter or harsh arc behaviour. The current is then increased in accordance with a pre-determined curve to facilitate the separation of the ball. When the weld metal is about to separate from the end of the electrode and to transfer to the weld pool (i.e. the short breaks), the power source drastically reduces the welding current. Droplet transfer happens at minimum current and thus limits spatter and other effects caused by the dynamic activity during restart of arc. After completion of the metal transfer and re-establishment of the arc, a current peak is applied to produce a plasma force which pushes down the weld pool and prevents an accidental short. The current then tails out to regulate the overall heat balance and the cycle starts again.

### 3.1.1.8 Advanced MIG welding techniques using reciprocating wire feeding

The other possibility to realize a MIG welding process with reduced heat input based on the short-circuit metal transfer mode is the reciprocating wire feed (RWF) technique. The wire is reciprocated in and out of the weld pool in synchronization with the current waveform, i.e. the heating arc is automatically activated and deactivated in order to systematically heat and cool the welding wire.

The key to RWF MIG welding is an accurate digital process control where the detection of a short circuit initiates an immediate withdrawal of the wire, interrupting the arc load. The wire movement must take place at a very high frequency and extreme precision.

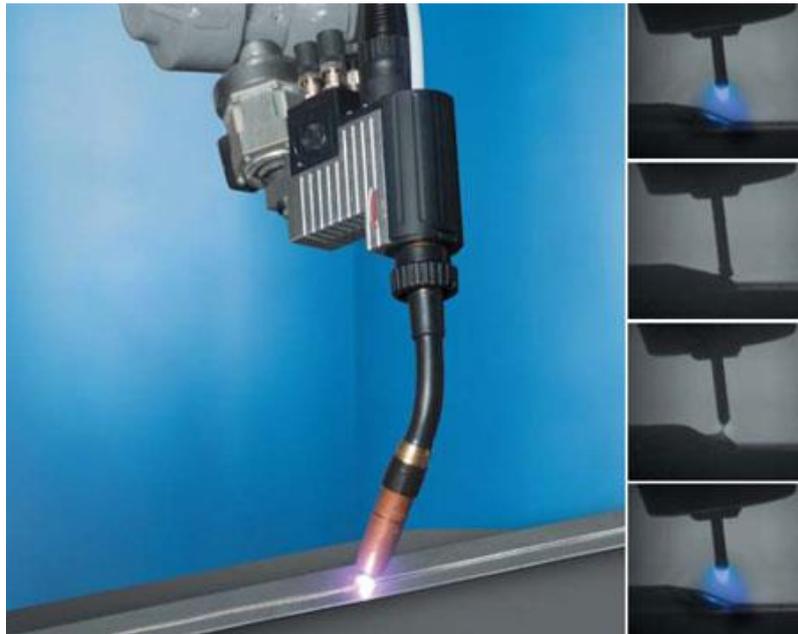


**Functional principle of reciprocating wire feeding**

(Source: Fronius)

During the arcing phase, a droplet is formed on the end of the wire and the filler wire is advanced towards the weld pool. The shorting phase begins when the wire with its molten droplet comes into contact with the weld pool. When the short circuit is detected, the digital process control interrupts the power supply and initiates the retraction of the wire. The retraction of the wire, in combination with the surface tension forces, causes the droplet to detach. Due to the slight retraction of the wire electrode, the short-circuit bridge breaks more easily and the duration of the short circuit is reduced ensuring a clean, spatter-free material transfer. Once the ball is separated, the wire motion is reversed and the process starts again.

In the RWF mode, heat is only introduced very briefly in the arcing period, after which thermal input is immediately reduced and metal transfer is essentially current-free. Thus RWF MIG welding generates only a fraction of the heat produced in the standard MIG welding process and also less heat than advanced, current-controlled short-circuit MIG welding where droplet transfer is achieved through the combination of the pinch force imposed by an increased current level and surface tension forces.



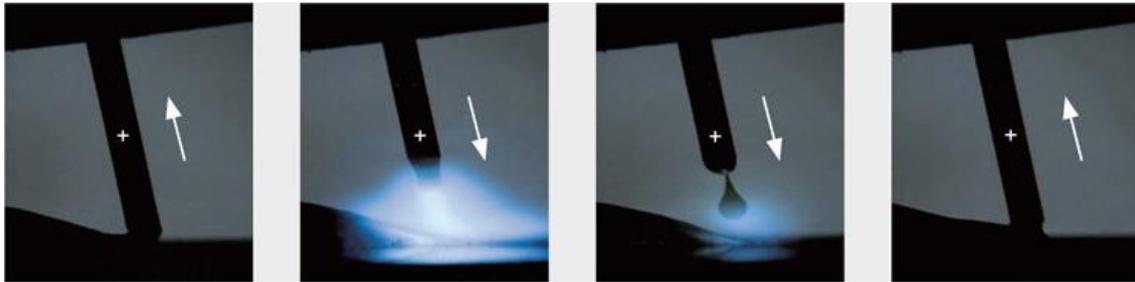
**Reciprocating wire feed MIG welding torch (CMT® process)**

**(Source: Fronius)**

However, RWF MIG welding is more complex than the conventional MIG welding process and its advanced short-circuit metal transfer variants. Equipment manufacturers include Jetline Engineering (Controlled Short Circuit, CSC), Fronius (Cold Metal Transfer, CMT), SKS Systems (micro-Mig), and Panasonic (Active Wire Process, AWP). Since a highly dynamic wire drive is required, the RWF technique is commonly applied as an automated process and used in combination with welding robots (partly also as a consequence of the need to manipulate a larger, heavier torch). Many equipment manufacturers offer pre-defined programs that enable synergic control of all welding parameters.

The various systems mainly differ in the wire feeding concept. One possibility is a high speed, precision stepper motor incorporated into the torch that controls both feeding direction and wire speed as used for example in Jetline's CSC system. Another possibility is the two wire drive system used in the Fronius CMT® process. The rapid forward and back wire movement is ensured by a gearless wire drive directly on the torch which is designed for speed whereas the more powerful, slower main wire feeder is responsible for the continuous wire feed. A buffer is used to convert the superimposed, high-frequency wire movement into a continuous wire feed.

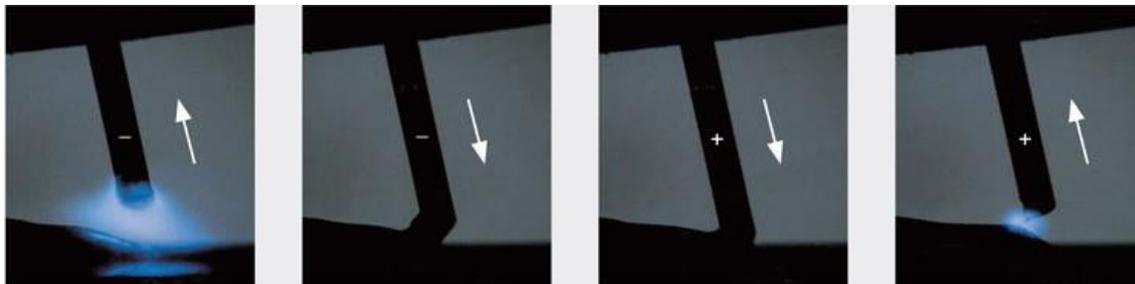
There are different options to exploit the potential of the RWF MIG welding technique. As an example, RWF and standard electrode positive pulsed MIG welding can be combined to produce more heat for thicker material welding. Introducing pulses in a controlled, adjustable way offers significant improvements in performance and flexibility.



**Combination of RWF and pulsing cycles (pulsed-arc positive)**

(Source: Fronius)

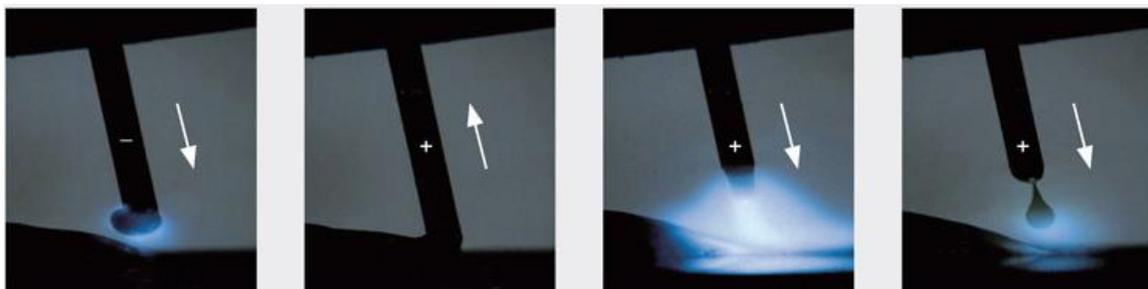
Another option is to operate the RWF MIG welding with alternating current (AC). The polarity of the welding current is made an integral part of the process-control and thus offers an even more tightly controlled thermal input. Polarity reversal takes place in the short circuit phase. Due to the negatively poled phase, the weld process achieves a higher deposition rate and better gap bridging. The positive cycles ensure controlled thermal input and precision droplet transfer. The relationship between the positive and negative cycles can be individually defined as required by each specific application.



**Combination of RWF and AC cycles**

(Source: Fronius)

RWF cycles can also be combined with negative electrode polarity alternating with positive polarity pulsing phases. During the negatively poled RWF phase, a higher deposition rate is obtained with lower thermal input. Pole reversal to the positively poled pulsing cycles takes place in the short circuit. In addition to the higher thermal input, the pulsing phase enables a non-short-circuiting droplet transfer. The relationship between the positive and negative process cycles is also freely selectable. This process variant achieves optimum arc control and absolute precision.



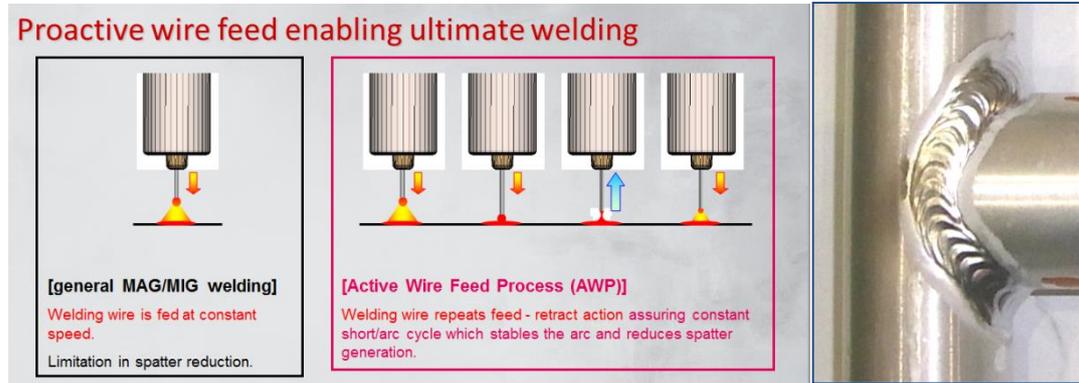
**RWF process combining negatively poled cycles and positively poled pulsing cycles**

(Source: Fronius)

Furthermore the RWF technique can be incorporated into a tandem MIG welding process.

Since material transfer in the RWF mode takes place with barely any current flow, light-gauge welding (0.3 - 0.8 mm) of aluminium sheets is perfectly feasible. At material thicknesses up to 3 mm, it outperforms conventional MIG and TIG welding processes by far. For seam welding, the work pieces are securely clamped and welded, and then any excess metal is removed by grinding. Most interesting is also the application of RWF MIG welding to join an aluminium component to steel using a special brazing process (see section 11.2.1.3).

Ultimately, RWF cycles can be combined with advanced current profile control methods. In this case, the current is programmed to squeeze the liquid bridge. When the welding system detects the necking sequence, the current is immediately lowered while the rearward movement of the wire assists in the droplet detachment, thus minimizing time in the short-circuit phase. The high precision of the droplet-detachment sequence ensures spatter-free metal transfer and guarantees that after every short circuit, a near-identical quantity of filler metal is melted off. The incorporation of the wire motion into weld process-control results in a higher process stability, offers the ability to bridge higher gaps and ensures a flaw-less weld appearance, specifically when welding thin-walled aluminium materials.



### **RWF MIG welding with advanced current control excels in the low thickness range (Source: Miller Welding Automation)**

Since the arc length is acquired and mechanically adjusted, the arc remains stable, independent of the work piece surface, the welding speed and the welding position. These advantages are obviously most interesting for robotic welding. Thanks to fully synchronized system components and consistent digitalization of the power source, robotic welding can be performed faster and with a higher degree of reproducibility. Information on the current status of the power source and on every weld seam can be used to monitor, analyse and document the welding process.

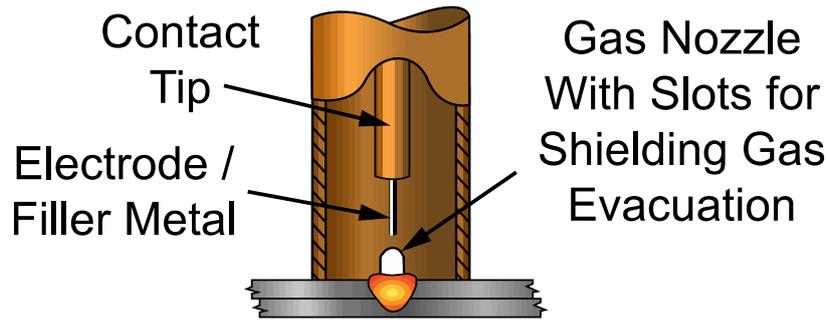


**Fully digitized power source designed to meet the demands of robot-assisted welding  
(Source: Fronius)**

### 3.1.1.9 MIG spot welding

MIG spot welding may be used to lap weld sheets by melting through the top sheet and fusing into the bottom sheet without moving the torch. The equipment used for spot welding is essentially the same as that used for conventional MIG welding, using the same power source, wire feeder and welding torch. The torch, however, is equipped with a modified gas shroud that enables the shroud to be positioned directly onto the sheet surface. The shroud is designed to hold the torch at the correct arc length and is castellated such that the shield gas may escape. The power source is provided with a timer so that when the torch trigger is pulled a pre-weld purge gas flow is established, the arc burns for a pre-set time and there is a timed and controlled weld termination. The pressure applied by positioning the torch assists in bringing the two plate surfaces together.

The process may be operated in two ways: (a) by MIG spot welding with the weld pool penetrating through the top plate and fusing into the lower one or (b) by plug welding where a hole is drilled in the upper plate to enable the arc to operate directly on the lower plate so that full fusion can be achieved. MIG spot welding method can be used as an alternative to resistance spot welding where there is insufficient access for a spot welder.



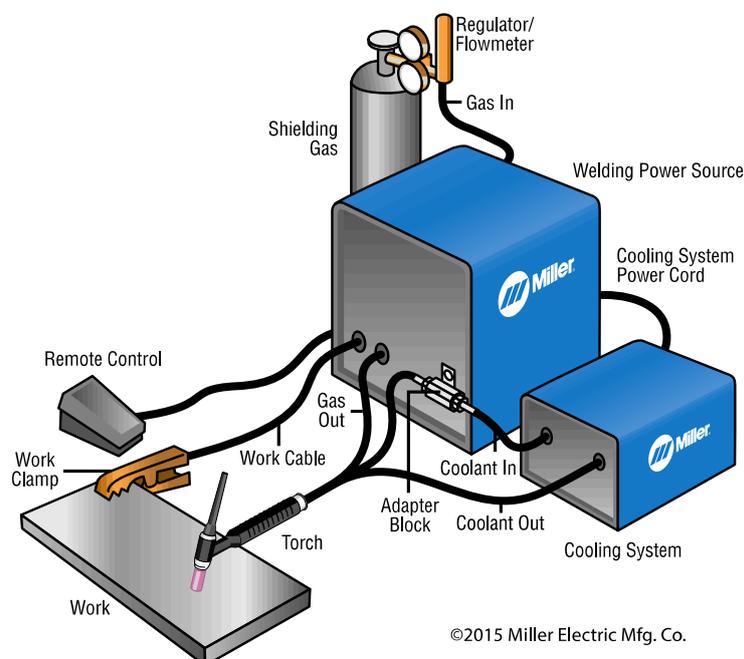
Schematic of the MIG spot welding process

(Source: Miller Electric Mfg. Co.)

Argon is the preferred shield gas choice as it produces a deep, narrow penetration. Argon also provides better arc cleaning than helium. Proper surface cleanliness is crucial to achieve defect-free welds.

### 3.2 Arc welding with non-consumable electrodes

The tungsten inert gas (TIG) welding process – often referred to as gas tungsten arc welding (GTAW) process – was developed earlier than the MIG (GMAW) welding process. For many applications, TIG welding has been replaced nowadays by MIG welding, primarily because of the increased welding speed when welding thicker sections. However, TIG welding is still widely used to join aluminium alloy products. The small, intense arc provided by the pointed electrode is ideal for high quality and precision welding. TIG welding is especially useful for welding thin materials, but requires significant operator skill and can only be accomplished at relatively low speeds. Generally, little or no post weld finishing is required.



Common components of a TIG welding system

(Source: Miller Electric Mfg. Co.)

TIG welding uses a non-consumable electrode made of tungsten and an inert shielding gas or gas mixture. The welding heat is generated by an electric arc between the tip of the electrode and the base metal. TIG welding is carried out with either alternating current (AC) or direct current (DC). For the majority of metals, TIG welding takes place using direct current with

negative electrode polarity (DC-EN). Aluminium, however, is generally welded using alternating current. Initially applied to all material thicknesses and joint types, TIG welding is today generally limited to join thin aluminium plates up to 7 mm thickness, although the DC-EN mode is suitable for welding thicknesses up to 25 mm.

A related process is plasma arc welding (see 3.2.2). Plasma arc welding also applies a non-consumable tungsten electrode, but uses a plasma gas to make the arc. The greater energy concentration offers higher welding speeds and results in lower geometrical distortions. However, the more concentrated plasma arc makes transverse control more critical. Thus plasma arc welding is generally restricted to mechanized processes.

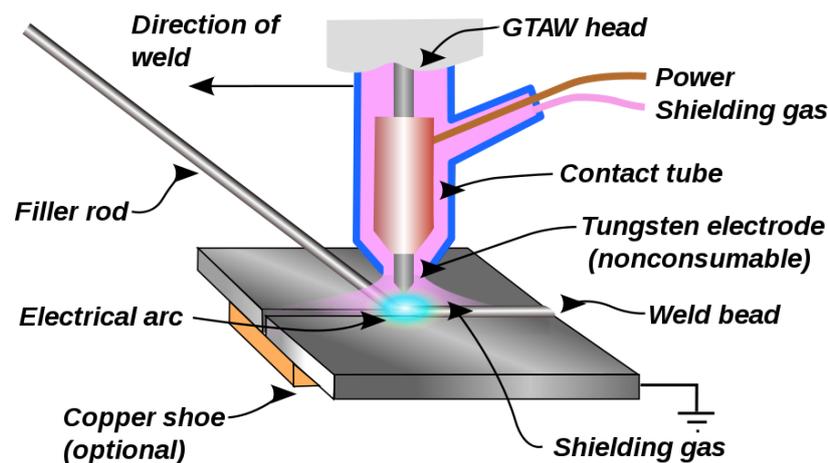
### 3.2.1 Tungsten inert gas (TIG) welding

At the core of a TIG welding torch is a non-consumable, temperature-resistant tungsten electrode through which the welding current is introduced to the weld zone. Between the pointed tungsten electrode and the work piece, the arc is formed in an inert atmosphere. The freely burning arc delivers the heat which is used to locally melt the base material and generate the weld. If applicable, it also melts the added filler metal.

Well prepared, close-fitting materials may need no filler metal to be effectively fused. But many aluminium alloys require the addition of filler material to maintain the metallurgical and mechanical properties of the weld (see 2.4). The filler wire is added separately to the weld pool, either manually or with a wire feed unit.

The shielding gas streams out of the welding torch through the collet body and is directed toward the weld by means of a nozzle which is fitted around the tungsten electrode. The shielding gas protects the hot tungsten electrode and the weld pool from chemical reactions with the surrounding air.

Ignition of the electrode normally takes place without the tungsten electrode touching the work piece. This requires a high-voltage source that temporarily switches on during ignition and provides an electric spark. The spark produces a conductive path for the welding current through the shielding gas and allows the arc to be initiated. An alternate way to initiate the arc is the "scratch start". Scratching the electrode against the work piece with the power on serves to strike an arc. However, scratch starting can cause contamination of the weld and electrode. Some types of TIG welding equipment offer a "touch start" mode where a spark is produced with a reduced voltage on the electrode (well below the limit that causes metal to transfer and contamination of the weld or electrode). As soon as a spark is detected, the power is immediately increased, converting the spark to a full arc.



#### TIG (tungsten inert gas) welding process

The TIG-welding method can be used manually, partly and fully mechanized as well as automatically. TIG welding generally provides a smooth weld bead with little undercut. In specific cases, MIG welded joints can be therefore dressed by TIG for improved fatigue life.

### 3.2.1.1 Tungsten electrodes

Tungsten electrodes are used when arc welding with the TIG or the plasma arc process because they can withstand very high temperatures with minimal melting or erosion. Tungsten electrodes usually contain small quantities (1 – 4 %) of other metal oxides which – compared to pure tungsten electrodes – can facilitate arc ignition, improve current-carrying capacity of the rod and increase arc stability as well as electrode life. The electrodes are produced by powder metallurgy and are formed to size after sintering.

Pure tungsten may be used in conjunction with transformer-based power sources for AC welding. For a broad variety of power source technologies, however, tungsten containing lanthanum, cerium, yttrium or zirconium oxides are primarily used. Thorium oxide has been used for many years and has been found most effective in reducing electrode degradation and increasing thermal efficiency. But legal requirements concerning the handling and utilization of radioactive thorium-containing materials impose high costs on manufacturers and their customers alike. Therefore, careful consideration should be given if the use of thoriated tungsten electrodes is justified. The general consensus is that cerium or lanthanum oxides are acceptable alternatives to thoriated tungsten.

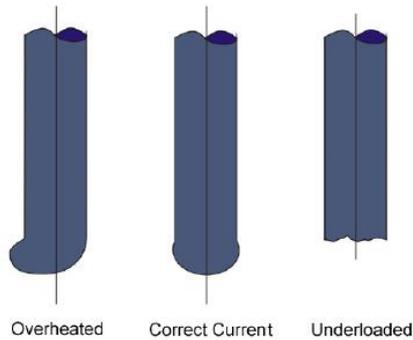
It is important to select the correct electrode type, diameter and tip angle for the level of the applied welding current. For AC welding of aluminium, cerium oxide containing tungsten electrodes are commonly used. Electrodes with lanthanum or rare earth oxide additions are recommended for applications which require slightly higher performance. The electrode diameter is determined by the thickness of the work piece and the current magnitude. As a rule, the lower the current, the smaller the electrode diameter and the tip angle should be chosen.



**Tungsten electrode tip prepared for AC use on an inverter welding power source (top) and slightly rounded after use (bottom)**

**(Source: Miller Electric Mfg. Co.)**

It must be noted that AC welding can generate a large amount of heat at the tip of the electrode. As a result, it is not uncommon for the pointed tip of the electrode to assume a hemispherical profile. Overheating or underloading of the electrode will produce unsatisfactory tip geometries.



### Formation of the correct electrode tip in alternating current welding with transformer based power sources

#### 3.2.1.2 Shielding gases

Only inert shielding gases such as argon, helium or their mixtures can be used since the tungsten electrode is at a very high temperature and therefore prone to chemical reactions with the environment. The choice of the shielding gas, as well as the current type and polarity, influence the heat transfer of the arc and affect the profile of the weld seam. This is predominately due to the physical characteristics of the gases and their respective thermal conductivities which strongly determine the shape of the arc (see section 2.5).

The most-used shielding gas for TIG welding of aluminium with alternating current is argon. It optimises the ignition properties and offers a calm and stable metal transfer. Helium raises the temperature of the arc which leads to a higher thermal input into the work piece. This can be utilised either for welding thicker materials or for increasing the welding speed in thin material. There is also a lower tendency for porosity due to the hotter weld pool with lower viscosity and better degasification possibilities. A disadvantage of helium is, however, the less stable arc and difficult arc ignition. Additionally, due to its lower density compared to argon and the surrounding air, helium will require higher flow rates to ensure adequate coverage.



#### Profile of the TIG weld pool for different shielding gases (same welding conditions):

- 100 % Argon (left)
- 50 % Ar / 50 % He (centre)
- 100 % Helium (right)

A compromise between the two different gases offer argon-helium mixtures. Effective combinations of helium and argon have been found to lie between 30 – 70 % of each respective gas. Most commonly used is a mixture of 50 % argon and 50 % helium. In addition to classic argon and the argon-helium mixtures, more advanced gas mixtures may also contain very small amounts (150 – 300 ppm) of nitrogen for additional arc stabilization.

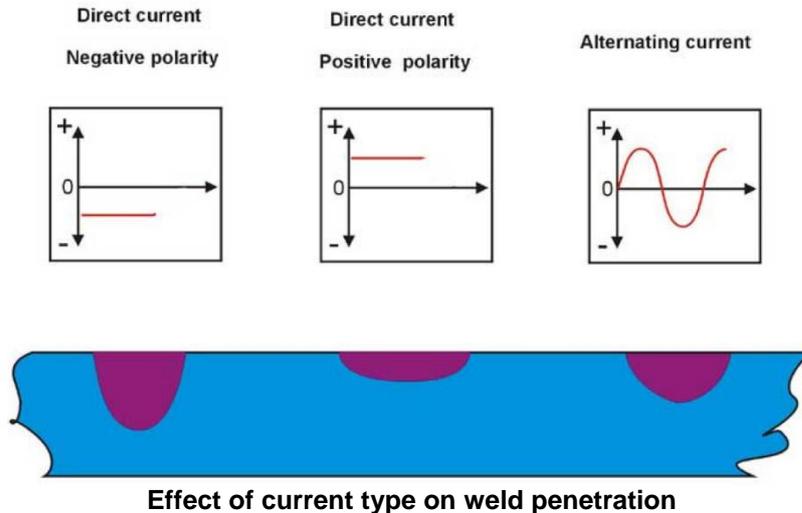
Pure helium or high helium content shielding gas mixtures are seldom employed except in TIG welding in the DC mode with a negative electrode where the increased heat is necessary to break up the oxide film. However, the DC-EN TIG welding technique is relatively seldom used in practice.

#### 3.2.1.3 Effects of polarity on weld penetration

The form of the weld pool and of the weld seam can be influenced by current type and electrode polarity. Alternating current (AC) is the most popular TIG welding method of aluminium, but direct current (DC) power can be employed for some specialized applications. Three types of arc generation are feasible:

- Direct current, electrode negative (DC-EN) → deep penetration
- Direct current, electrode positive (DC-EP) → low penetration

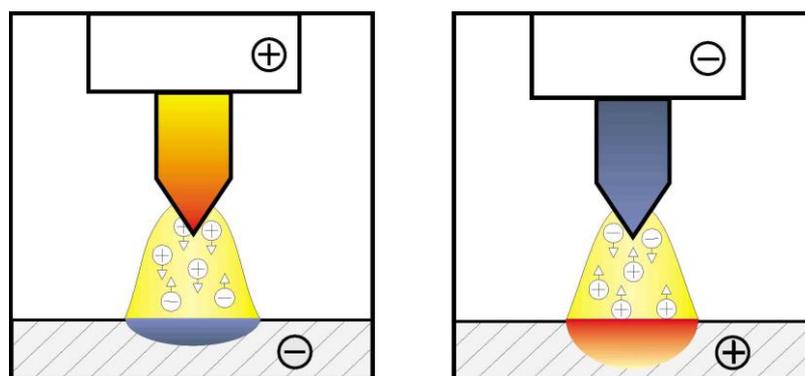
- Alternating current (AC) → medium penetration.



TIG welding in the direct current electrode negative mode (DC-EN) results in relatively deep and narrow weld penetration, and very little, if any, arc cleaning during welding. About 80 % of the heat is generated in the base material and about 20 % at the electrode. Typically used with pure helium shielding gas, this method is capable of welding much greater material thicknesses. However, only mechanised welding is recommended since a short arc (< 1 mm) is required. Because of the absence of an arc cleaning effect, fusion of the joint faces occurs mainly by melting/break-up of the oxide film, i.e. there is an increased risk of welding discontinuities (oxide inclusions and fusion defects).

Using TIG welding in the direct current electrode positive mode (DC-EP), about 20 % of the heat is generated in the work piece and 80 % at the electrode, i.e. arc cleaning is excellent, but there is very shallow weld penetration. This is the least used TIG welding method as it places a heavy thermal load on the tungsten electrode. It requires large diameter electrodes with wide angled tips, but nevertheless often leads to excessive electrode heating.

The AC arc offers a compromise of the characteristics of positive and negative electrode polarity. It provides appropriate cleaning for most applications, extends the electrode lifetime, and divides the arc heat more evenly between electrode and weld pool, leading to medium weld penetration. Some power supplies enable the use of an unbalanced alternating current wave by modifying the exact percentage of time that the current spends in each state of polarity, giving even more control over the amount of heat and cleaning action.



**TIG-AC welding process with periodic cleaning/melting actions**

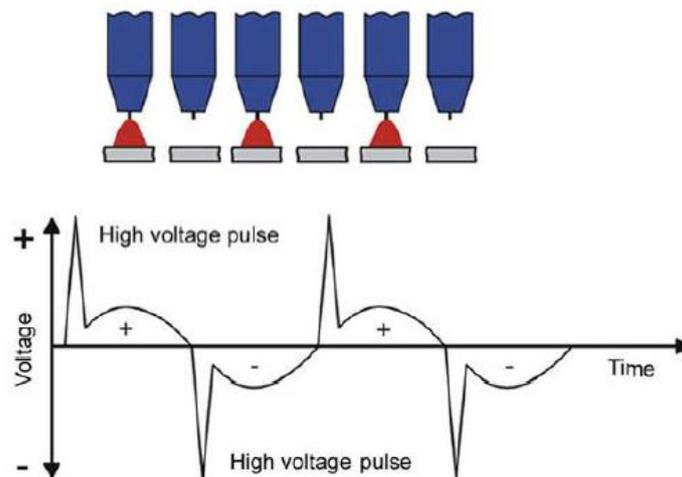
The respective application areas of the different TIG welding modes for aluminium are:

- TIG (AC) - conventional TIG welding: Generally used for thicknesses up to 6 - 10 mm, provides good cleaning action of the arc.
- TIG-He (DC-EN): Requires pre-cleaned surfaces of the work piece and generally fully automatic welding because of the short arc length. It offers higher welding speeds, lower thermal stresses and lower thermal load of the electrode than TIG (AC).

- TIG (DC-EP): Only used for very thin gauge materials due to the large thermal load of the electrode in this polarity.

Historically, alternating current has posed an obstacle to TIG welding because the arc would frequently extinguish when the current reaches zero before reversing direction. Without any current passing between the tungsten electrode and the base metal, the arc simply goes out, i.e. it is necessary to start the arc at the beginning of each half cycle. Consequently transformer based technology requires a high frequency spark of several thousand volts which last for a few microseconds at the beginning of the positive and negative half cycles to encourage ignition. The high frequency sparks cause the electrode – work piece gap to break down (“ionize”) and thus enable current flow.

The high frequency power source necessary for arc ignition, however, represents a potential hazard to the sensitive electronic equipment in the surrounding. This problem was eliminated with the introduction of advanced inverter-based power sources and the application of the pulsating square wave technique. Thus conventional AC TIG welding finds today much less application.

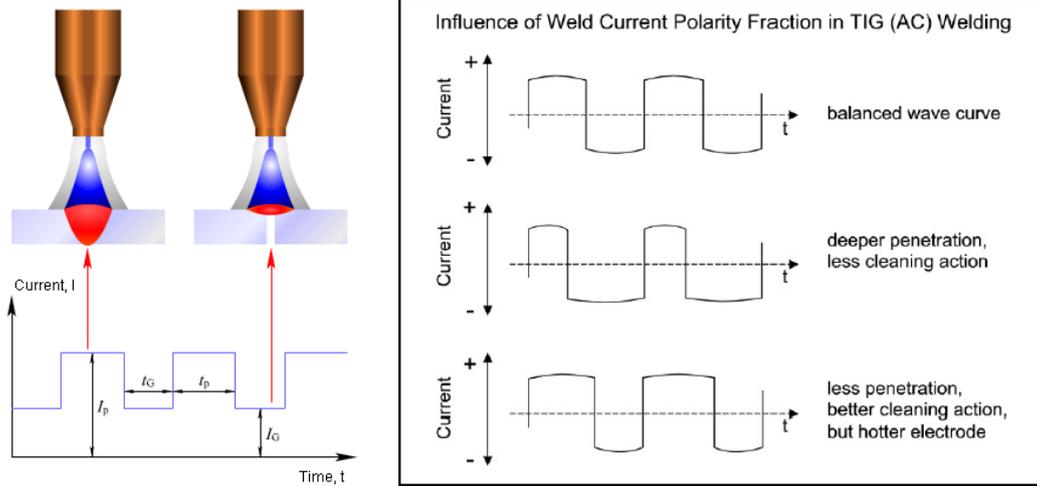


**Arc burning process in TIG welding with alternating current**

### 3.2.1.4 Square wave (“pulsed”) and frequency controlled TIG (AC) welding

The square wave technology eliminates the tendency for the arc to extinguish when the current comes to a halt as it reverses direction by making the transition very quickly. This greatly improves the stability of the arc and makes the square wave technology the preferred method for TIG welding aluminium.

The most important weld parameters are the pulse current ( $I_p$ ), the background current ( $I_G$ ), the pulse current time ( $t_p$ ), the background current time ( $t_G$ ) and the pulse frequency  $f_p = 1 / t_c$ , where:  $t_c$  = duration of period.



**Pulsating square wave AC welding**

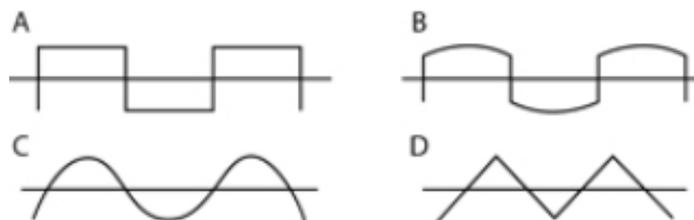
During the high current impulse, a large amount of heat is generated in the welding area which results in the fusion of the work material and, if applicable, the filler wire. In the impulse pause where a low current is preset, only a little heat is transmitted into the work piece, thus the weld pool stays comparatively cool. The low background current only serves to maintain the arc in order to avoid interruptions and ignition difficulties.

With square wave AC welding, the weld heat input can be considerably changed by the choice of times and current values, allowing significantly better control of the weld pool. Thus the application range of the TIG process can be extended to low power values, i.e. the material thicknesses can be reduced, weld drop-through can be prevented and the weld seam appearance can be improved. In the extreme case, a weld seam may even consist of fusion welding points which lie next to each other or overlap.

But the re-ignition of the arc by the utilization of a steep-sided, square wave has also disadvantages. The main problem is that the change to the arc column resulting from the current change causes an acoustic emission (“noise”).

The recent introduction of inverter-based power sources enabled the development of advanced square wave techniques which further decrease the time it takes for the current to reverse direction. In addition, they also offer more possibilities for the selection and control of the current profile.

Modern power sources offer the selection between different waveforms which affect the arc and weld pool characteristics as well as the penetration profile in a different way. But also the resulting arc “noise” essentially depends on the waveform.



**Different waveforms change the TIG welding characteristics**

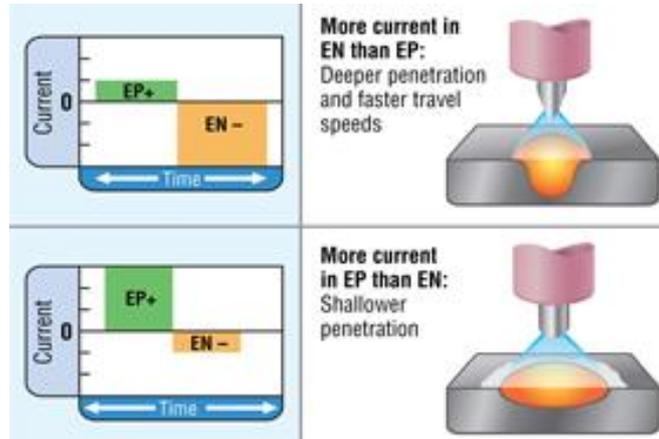
A very square wave (A) produces a smooth, stable arc with great directional control. It forms a fast-freezing weld pool with deep penetration and fast travel speeds. A common issue is porosity, especially on thick aluminium parts, because the molten metal pool solidifies too quickly. Slowing down the welding speed will normally resolve this issue. However, the noise level of a pure square wave is very high.

The "sinusoidal" (C) wave with fast transition through the zero amperage point offers a soft arc, i.e. similar to a conventional power source. It provides good wetting action and actually sounds quieter than any other waveform. The triangular wave (D) leads to quick weld pool formation, but reduces the overall heat input into the weld. It is especially beneficial for welding thin aluminium parts.

## THE ALUMINIUM AUTOMOTIVE MANUAL

The soft square waveform (B) maintains the benefits of the true square wave, but the arc noise is reduced and control of the weld pool is improved. For most applications, this waveform is ideal. In practice, an appropriate adjustment of the soft square waveform is generally used to set the physically quietest arc for any specific welding current.

Furthermore, independent amperage (or amplitude) control allows the EP and EN current level to be set differently. A current waveform with greater EN than EP creates a narrow bead with deeper penetration and no visible cleaning action. A current waveform with greater EP than EN leads to a wider bead with less penetration and clearly visible cleaning action. Increasing EN while maintaining or reducing EP also takes heat off of the tungsten electrode and more precisely directs it into the weld.



**Effects of independent current control in square wave AC welding**

(Source: Miller Electric Mfg. Co.)

AC balance control adjusts the amount of time spent in the penetration (EN) and cleaning action (EP) portions of the cycle. Extending the EN portion narrows the weld bead, achieves greater penetration, and may permit increased travel speeds. It also reduces the excessive etching zone beyond the toes or edges of the weld. Reducing the EN portion of the cycle widens the weld bead. It produces a greater cleaning action and minimizes penetration, which may help prevent burn-through on thin materials.

Waveform	Effect on Bead	Effect on Appearance
<p>75% EN</p>	<p>Reduces balling action and helps maintain point</p>	<p>Minimum Visible Oxide Removal (etching)</p>
<p>50% EN</p>	<p>Increases balling action of the electrode</p>	<p>Visible Oxide Removal (etching)</p> <p style="text-align: right; font-size: small;">©2015 Miller Electric Mfg. Co</p>

**Effects of AC balance for square wave AC welding**

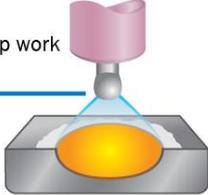
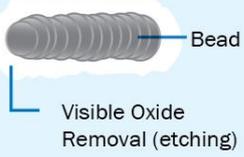
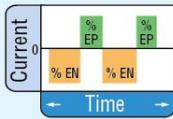
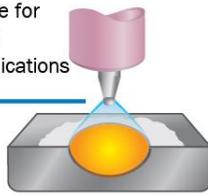
(Source: Miller Electric Mfg. Co.)

An increased EN portion also reduces the balling action, increases the lifetime of the tungsten electrode and may permit the use of a smaller electrode to more precisely direct the heat into the weld. Reducing the EN cycle increases the balling action because more heat is directed into the electrode. This creates a large ball at the end of the tungsten and causes the arc to lose stability, making it hard to control the arc weld pool.

Depending on the power source, the balance may be typically adjusted in the range of 50 - 75 % EN mode. The preferred range for clean aluminium work pieces is 68 - 75 % EN.

## THE ALUMINIUM AUTOMOTIVE MANUAL

The introduction of inverter power sources also allowed to exploit the variability of the pulse frequency. Traditional power source frequencies are dictated by the input power (50 Hz in Europe, 60 Hz in the United States) while inverter power sources have a greater ability to transform the electricity to the desired output frequency. Adjusting the AC frequency provides excellent control over bead appearance and penetration profile.

Waveform	Effect on Bead	Effect on Appearance
<p>60 Hz</p> 	<p>Wider profile ideal for buildup work</p> 	
<p>120 Hz</p> 	<p>Narrower profile for fillet welds and automated applications</p> 	 <p>©2015 Miller Electric Mfg. Co</p>

### Effects of Frequency for AC GTAW

(Source: Miller Electric Mfg. Co.)

Up-to-date inverter-based power sources offer AC output frequencies between 20 Hz and 400 Hz. In general, 120 to 200 Hz provides an ideal frequency for most aluminium welding applications. The increased frequency causes the current to change direction more often and the arc cone has less time to expand. It produces a more focused arc with increased directional control and a narrower bead and cleaning area which improves performance when welding in corners, on root passes, and in fillet welds. An arc cone at 400 Hz is even tighter and more focused. The result is a significantly improved arc stability, ideal for fit ups requiring precise penetration and reduced distortion. On the other hand, a lower frequency softens the arc and results in a wider weld pool. This removes impurities well and transfers the maximum amount of energy to the weld piece, which speeds up applications requiring heavy metal deposition.

#### 3.2.1.5 TIG welding equipment

An ideal TIG AC/DC power source possesses a virtually constant output current to control the length of the arc. A constant current power source is essential to avoid excessively high currents being drawn when the electrode is short-circuited on to the work piece surface. This may happen either deliberately during arc starting or inadvertently during welding. If a flat characteristic power source is used, any contact with the work piece surface would damage the electrode tip or fuse the electrode to the work piece surface.

Continuous current adjustment is required for proper adaption to different material thicknesses. Modern inverter power sources offer the additional advantage of a fast reaction to changes in the welding process. Many power sources also allow the user to select the current waveform and to properly adjust the specific current profile characteristics.



## AC/DC power source for TIG welding offering tailored arc control

(Source: Miller Electric Mfg. Co.)

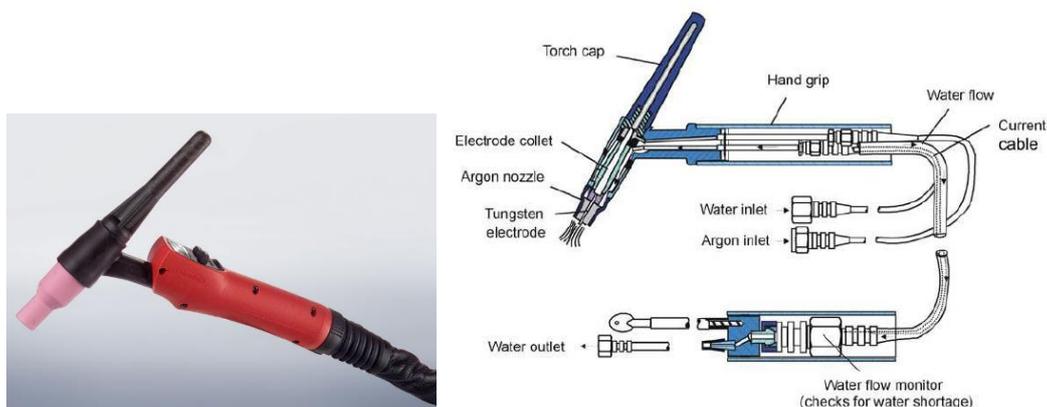
Depending on the severity of the thermal load, TIG welding torches are either gas-cooled (for light duty applications) or water-cooled. For welding currents >100 A, water cooling of torch and current cable is commonly used. The gas nozzle is made of metal or ceramics and has to be insulated against electricity conducting parts. The electrode protrudes about 2 to 4 mm beyond nozzle. They are cooled by the shielding gas.



## Gas-cooled TIG welding torch

(Source: Miller Electric Mfg. Co.)

Gas-cooled welding torches are cooled by the shielding gas which flows through, while water-cooled welding torches also require a pump and heat exchanger.



## Water-cooled TIG welding torch

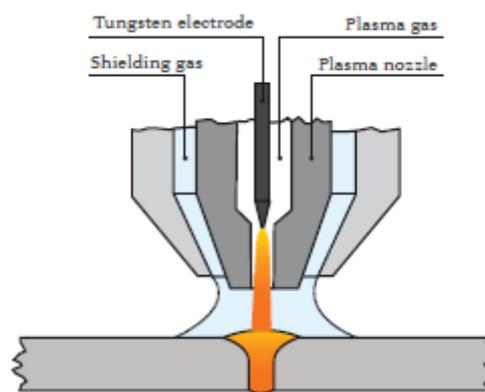
(Source: Fronius)

The filler metal is added to the weld pool separately from the torch. There are also TIG welding torches with an integral device for mechanised wire feeding.

### 3.2.2 Plasma welding

The plasma welding process is basically very similar to the TIG process, but has a number of advantages which make it an interesting alternative to laser welding, especially on sheets and other components with a sheet thickness of up to 8 mm.

The difference is that in plasma welding, the arc consists of a plasma (i.e. a gas with positive charge carriers (ions) and negative charge carriers (electrons)). The plasma arc is constricted with the help of a water-cooled, fine-bore copper nozzle which squeezes the arc, increases its pressure, temperature and heat intensity and thus improves arc stability, arc shape and heat transfer characteristics. Additionally, plasma welding has greater torch standoff. Being enveloped in plasma gas, the tungsten electrode also has a longer service life than in TIG welding.



**Plasma arc welding process**

(Source: Fronius)

The process employs two separate inert gas flows. By positioning the electrode within the body of the torch, the plasma gas can be separated from the shielding gas envelope. The plasma gas flows through the orifice at relatively low pressure and flow rate; it becomes ionized and forms the arc plasma. The pressure of the orifice gas is intentionally kept low to avoid weld metal turbulence, but this low pressure is not able to provide proper shielding of the weld pool. Therefore a shielding gas flows through the outer nozzle at comparatively higher flow rates and shields the arc plasma as well as the molten weld from the atmosphere. These gases can be of the same or of differing composition. The plasma gas is normally argon, whereas for shielding, argon or argon/helium mixtures are used.

Filler metal may or may not be added. If a filler metal is necessary, an automated feed system is usually added to the torch.

Plasma arc welding process can be divided into two basic types:

- **Non-transferred arc process:** The arc is formed between the electrode (negative) and the water cooled constricting nozzle (positive). The arc plasma comes out of the nozzle as a flame. The arc is independent of the work piece and the work piece does not form a part of the electrical circuit. Compared to a transferred arc plasma, the non-transferred arc plasma possesses a lower energy density.
- **Transferred arc process:** The arc is formed between the electrode (negative) and the work piece (positive). A transferred arc possesses high energy density and plasma jet velocity, it is used for welding at high arc travel speeds. For initiation, a pilot arc is established between the electrode and the nozzle. This arc is then transferred to the metal to be welded and the main current starts to flow, thus igniting the transferred arc. The pilot arc system ensures reliable arc starting and, as the pilot arc is maintained between welds, it obviates the need for a high frequency pulse which may cause electrical interference.

The plasma exits the orifice at high velocities (approaching the speed of sound) and a temperature up to 28,000 °C or higher. Characteristic for the plasma arc is the strong temperature drop from the arc core towards the outside (in order to avoid melting of the constricting copper nozzle). Another difference compared to the TIG welding process can be observed visually: the TIG arc is conical and the plasma arc is cylindrical.

The plasma torch delivers a high concentration of heat to a small area, offering higher welding speeds and resulting in lower geometrical distortions. The size and the type of nozzle tip are selected depending upon the metal to be welded, weld shapes and desired penetration depth. With high performance welding equipment, the plasma process produces exceptionally high quality welds.

Three operating modes can be produced by varying bore diameter and plasma gas flow rate:

- **Micro-plasma (0.1 to 15 A)**

The micro-plasma arc can be operated at very low welding currents. It was traditionally used for welding thin sheets (down to 0.1 mm thickness). The needle-like, stiff arc minimises arc wandering and distortion.



**Micro-plasma welding**

(Source: Fronius)

- **Medium current (15 to 200 A)**

At higher currents, the process characteristics of the plasma arc are similar to the TIG arc, but because the plasma is constricted, the arc is stiffer. Medium current plasma arc welding is an alternative to conventional TIG welding. The advantages are deeper penetration and greater tolerance to surface contamination including coatings. The major disadvantage is the bulkiness of the torch, making manual welding more difficult.

- **Keyhole plasma (over 100 A)**

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

Compared with TIG arc welding, keyhole welding offers higher welding speeds and deeper material penetration. The normal method is to use the keyhole mode with filler metal to ensure a smooth weld bead profile with no undercut. The filler metal is added at the leading edge of the keyhole.

As the welding parameters, plasma gas flow rate and filler wire addition must be carefully balanced to maintain the keyhole and weld pool stability, this technique is only suitable for mechanised welding. The slope-out of current and plasma gas flow must be carefully controlled to close the keyhole without leaving a hole while terminating the weld in the structure.



**Keyhole plasma welding**

**(Source: Fronius)**

The plasma arc is normally operated with a DC power source. With a sine wave AC current, the plasma arc is not readily stabilised. However, for aluminium welding, the AC square-wave mode is commonly used and provides good results. Special modifications of waveform, i.e. a reduction of the duration of electrode positive polarity, allow to keep the electrode sufficiently cool in order to maintain a pointed tip and achieve arc stability.

In plasma arc welding, the electrode tip diameter is not as critical as for TIG welding. More critical is the plasma nozzle bore diameter. A bore diameter which is too small for the current level and plasma gas flow rate will lead to excessive nozzle erosion or even melting. On the other hand, a too large bore diameter may give problems with arc stability and maintaining a keyhole.

A further development is the variable-polarity plasma welding process. It combines the advantages of plasma arc welding with the additional benefits of arc cleaning, provided by periodic bursts of positive electrode energy. Variable polarity plasma welding has relatively low arc-travel speeds when compared to other arc welding methods and especially compared to MIG welding, but the fact that a single pass will replace multiple passes needed by other methods sometimes motivates its use.

### 3.3 Arc stud welding

Arc stud welding is a welding process in which a metal fastener (weld stud) is attached to a work piece by heating both parts with an electric arc. For welding, the fastener is positioned using a stud gun. When the operator activates the stud gun trigger, the sufficiently heated metal fastener is joined to the work piece without any filler metal. The welding time is less than one second, typically measured in milliseconds. One end of the fastener is prepared for welding. Shielding gases or flux may or may not be used to protect the weld.

There are two basic power supplies used to create the arc for welding studs. One type uses DC power sources similar to those used for gas-shielded metal arc welding ("arc stud welding"). The other type derives the heat from an arc produced by the rapid discharge of electrical energy stored in a bank of capacitors ("capacitor discharge stud welding"). The capacitor discharge method with its significantly shorter process time permits the welding of more dissimilar metals and alloys than arc stud welding. For either process, a wide range of stud styles is available.

The arc may be established either by rapid resistance heating and vaporization of a projection on the stud weld base ("gap ignition") or by drawing an arc as the stud is lifted away from the work piece ("lift ignition").

Stud welding produces full cross-sectional welded, high-quality attachment points that resist breaking or loosening. Bolts and similar attachments can be joined to aluminium sheets, extrusions or castings with single side access and without drilling holes or back-side support. However, conventional steel stud welders cannot be used for aluminium since its high heat dissipation asks for a power supply with a higher current capacity.



**Arc stud welding using a spotter on aluminium**

(Source: Cebora)

### 3.3.1 Arc stud welding with lift ignition

Arc stud welding with lift ignition is also called drawn arc stud welding since the arc is drawn between the stud and the work piece. The necessary heat is developed by a DC arc between the stud (electrode) and the work piece. Welding time and plunging of the stud into the molten weld pool to complete the weld are controlled automatically.



**Drawn arc stud welding process**

(Source: HBS)

Drawn arc stud welding generates high-quality welds and is particularly suitable when high demands relevant to safety regulations are made on the welding quality. The actual welding process consists of three steps:

- The stud tip is placed in contact with the work piece.
- The stud is lifted off the work piece while the current is flowing, thus creating a secondary (pilot) arc between stud tip and work piece.
- After a pre-determined period, the main current is allowed to flow. The ignition of the main arc creates a molten surface between the stud and work piece.
- The stud is plunged into the molten pool and the welding current is switched off. The weld pool solidifies and a cross-sectional joint is formed.

A welding rectifier serves as energy source and provides the continuous welding current which can be regulated with respect to weld time and power. The welding time amounts to  $\leq 0.1 - 1$  seconds.

Because arc stud welding time cycles are very short, the heat input into the base metal is very small compared to conventional arc welding. Consequently, the weld metal and heat affected zones are very narrow and distortion of the base metal at stud locations is minimal.

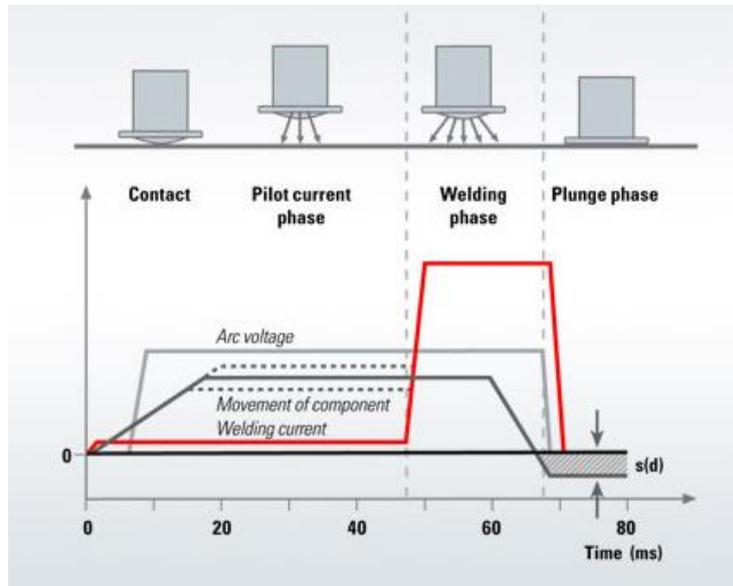


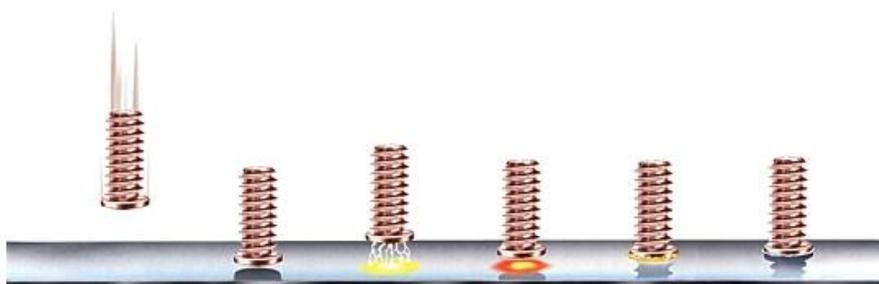
Illustration of the drawn arc stud welding process

(Source: Tucker)

A number of standard stud designs are commercially produced. Fasteners designed for arc welding often show a small tip which extends from the base of the fastener. This tip facilitates arc initiation and ensures precise weld time control for consistent, automatic welding. When selecting a stud, it is important to recognize that some of its length will be lost due to welding as part of the stud and the base metal melt. Molten metal is then expelled from the joint. When properly formed, the resulting flash indicates complete fusion over the full cross section of the stud base and suggests that the weld is free of contaminants and porosity.

Studs applied by arc stud welding often require a disposable ceramic arc shield (“ferrule”) around the base. It surrounds the stud to contain the molten metal and to shield the arc. At the end, the ferrule is broken away and discarded. Aluminium studs, however, do not use a ferrule; they usually rely on an inert gas (argon or helium) to protect the molten metal from the atmosphere and to stabilize the arc. But this approach is normally limited to production type applications because a fixed setup must be maintained and the welding variables must be closer controlled. Shielding gas mixtures of argon and 25 - 50 % helium at 2 - 4 l/min are recommended. The rapidly cooling weld cannot be completely avoid porosity in the weld zone. However, the amount of porosity can be minimised by proper surface preparation and optimised gas shielding.

Another possibility to avoid the use of ferrules is short cycle welding. A high weld current is applied for a very short time to minimize oxidation of the molten metal. Short cycle welding (welding time < 0.1 s) is generally limited to small studs. Since no ceramic ferrules are required, short duration stud welding can be easier adapted to automatic processes.



Short cycle drawn arc stud welding

(Source: HBS)

For lift ignition stud welding, the minimum wall thickness of the substrate is 1 - 2 mm. Due to low thermal stresses, geometrical distortion of the substrate can be reduced to a minimum,

there is very little to the reverse side of the substrate. Nevertheless, drawn arc welding typically causes more reverse-side marking compared to stud welding with tip ignition.

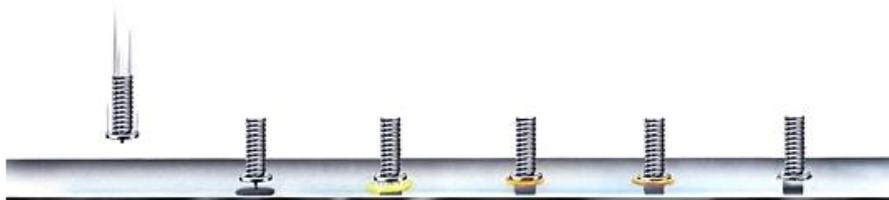


### Stud welding with lift ignition; studs and ferrules are available in a variety of shapes, sizes and materials

Various combinations of stud and substrate materials are possible. In case of aluminium substrates, prior removal of the oxide layer by mechanical (brushing, grinding) or chemical (alkaline etching) measures is necessary to avoid imperfect welds. Another possibility would be to reverse the plasma field to clean the surface and then reverse to the original polarity for stud welding.

### 3.3.2 Arc stud welding with tip ignition

In the process variant, the stud is positioned in a defined and adjustable distance above the work piece. After triggering the welding process, the stud is accelerated by a spring to the plate surface. As soon as there is contact between the ignition tip and the work piece, the current circuit is closed. The rapidly increasing current vaporizes the ignition tip and ignites the arc. During or immediately following the electrical discharge, pressure is applied to the stud, plunging its base into the molten pool of the work piece. As soon as the stud contacts the work piece, the current is cut and the molten zones join and solidify. Due to the extremely short welding times and the small amount of molten metal expelled from the joint, aluminium stud welding becomes feasible without using a shielding inert gas atmosphere or a ceramic ferrule.



### Capacitor discharge stud welding with tip ignition (gap welding)

(Source: HBS)

For stud welding with tip ignition, the required energy is generally stored in a capacitor battery and discharged through the ignition tip of the welding elements within an extremely short time period (1 - 3 milliseconds).



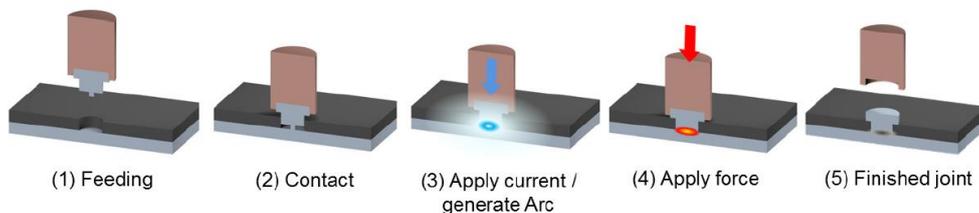
**Capacitor discharge stud welding unit (left) and stud welding gun (right)**

**(Source: HBS)**

The capacitor discharge technology is mainly suited for applications requiring small to medium sized studs. Owing to the low weld penetration (approximately 0.1 mm), it can be used for stud welding on thin-walled aluminium sheets with a minimum thickness of 0.5 mm. No traces of welding such as geometrical distortion, pressure marks, discoloration or deformation are visible on the reverse side of sheet. Even a discoloration of a painted backside can be avoided.

### 3.3.3 Arc element welding

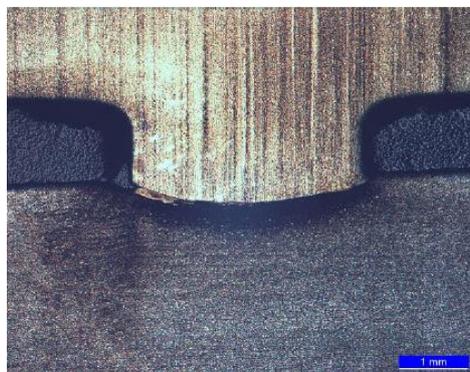
In arc element welding (“stud welding with an auxiliary joining part”), a short auxiliary joining part is used. The top sheet must be perforated. There is no direct joint between the top sheet and the bottom sheet, but the auxiliary joining part fixes the top sheet onto the carrier sheet in a mainly form-fitting and partially force-fitting joint. A welded joint is created only between the auxiliary joining part and the carrier sheet. Both drawn arc and tip ignition stud welding variants can be applied.



**Arc element welding (with tip) processing scheme**

**(Source: LWF Paderborn)**

This joining technique (which is still under development) is particularly suited to join different materials. The following figure shows a cross section through an arc element welded joint which connects a carbon reinforced fibre composite panel (top sheet, thickness 1.5 mm) to a high strength steel sheet (bottom sheet, thickness 2 mm).



**Joint between dissimilar materials produce by arc element welding**

**(Source: LWF Paderborn)**

## 3.4 Other arc welding techniques

### 3.4.1 Shielded metal arc welding

Prior to the development of the inert gas welding processes, arc welding of aluminium was mainly restricted to shielded metal arc welding, also known as manual metal arc welding or stick welding. An electric current is used to strike an arc between the base material and a consumable electrode rod. The electrodes are straight lengths of aluminium alloy rod, coated with flux. During welding, the flux dissolves the aluminium oxide surface layer both on the base alloy and the welding rod. Some of the flux components vaporize in the arc to form shielding gases which help to stabilise the arc and shield the arc and the weld pool from the surrounding atmosphere. The electrode core itself acts as filler material.

The process is very versatile, requiring little operator training and inexpensive equipment. However, welding times are rather long since the electrodes must be frequently replaced. When welding aluminium, the process is rather limited due to arc spatter, erratic arc control and limitations on thin material. A major problem with shielded metal arc welding of aluminium is corrosion caused by flux entrapment and porosity of the resulting welds. Furthermore there are no electrodes available for welding aluminium alloys with high magnesium content. Also electrodes, once exposed to the air, begin to absorb moisture into the flux, which eventually corrodes the aluminium core and produces excessive porosity problems.

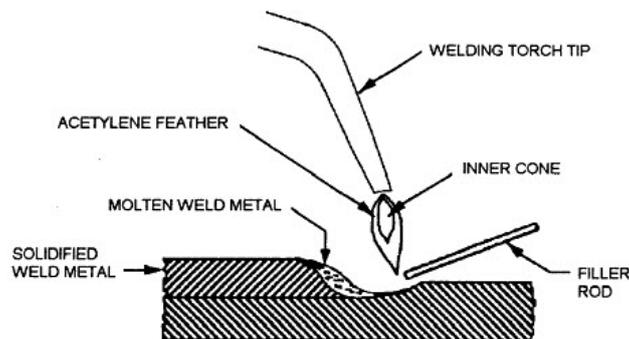


**Shielded metal arc welding**

Current welding codes and standards for aluminium structures do not recognise this welding technique as being suitable for production. Nevertheless it is today still used for small repair work.

### 3.4.2 Oxyfuel gas welding

One of the oldest welding processes is oxyfuel gas welding. It relies on the combustion of oxygen and acetylene. When mixed together in correct proportions within a hand-held torch or blowpipe, a relatively hot flame is produced with a temperature of about 3,200 °C. Welding is generally carried out using the neutral flame setting which has equal quantities of oxygen and acetylene.



**Oxyfuel gas welding**

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Prior to the development of the inert gas welding processes, it was widely used for welding aluminium, but has only limited applications today. For aluminium, an active flux must be used to remove the surface oxide and shield the weld pool. One of the problems with this welding process is that the flux is hygroscopic and becomes corrosive to aluminium. Therefore, any flux residue must be removed after welding to minimise the corrosion risk. Another disadvantage is the excessive heat input, i.e. the mechanical strength of the welded joint tends to be lower, the heat affected zone is very wide and distortion tends to be extreme. Welding is only practical in the flat and vertical positions.