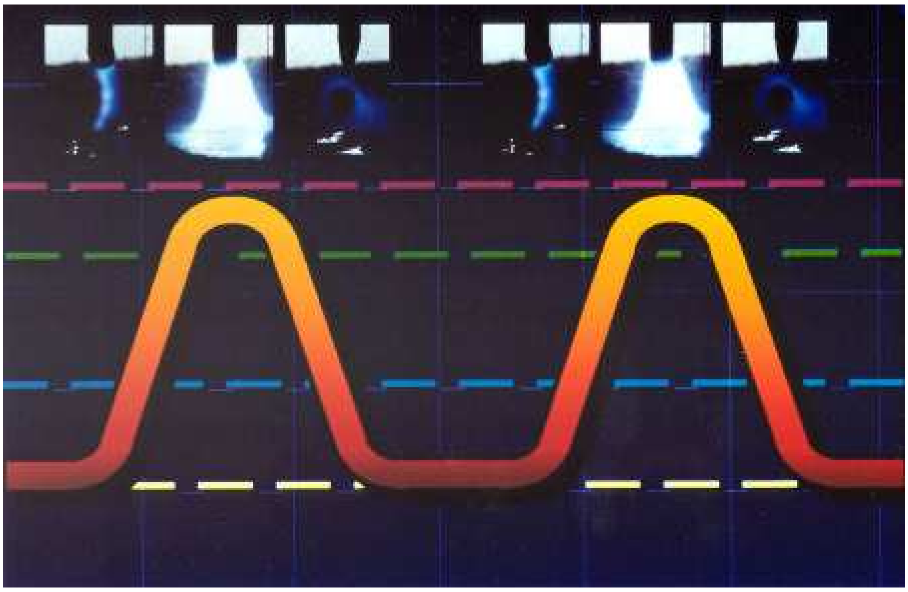
# Pulsed MIG-welding



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# Pulsed MIG welding

Pulsed MIG/MAG welding, or pulsed arc MIG welding, is a method of welding that uses current pulses from the power source to control transfer of the droplets of molten filler material in the arc in such a way as to produce a stable and spatter-free arc, even with low welding data. The method was developed in the 1960s by J. C. Needham at TWI (The Welding Institute) in the UK. However, it was difficult at that time to produce power sources that were sufficiently fast. As a result, the first power sources used part of the sine wave for creating their pulses, which meant that the pulse frequencies could be varied only in fixed steps.

It was not until the inverter power source was developed at the end of the 1970s that pulsed arc welding became more feasible. However, even so, it was the introduction of digital process control that has really made the method widely accessible. The technology used is referred to as 'synergic pulsed arc welding', with the word 'synergy' indicating a method of facilitating setting up the equipment by enabling the power source automatically to select appropriate pulse parameters. As the welder increases or decreases the wire feed speed, the other parameters are adjusted in order to maintain a suitable arc.

## Background

With ordinary MIG/MAG welding, without pulsed arc control, it is necessary to increase the welding current above a certain critical limit - generally above 200 A - in order to be able to produce a stable spray arc. Below this current value, it is difficult to get the droplets to release from the filler wire.

### Short arc welding

One solution to the problem of getting the droplets of molten metal to transfer to the weld pool at low welding currents is to use short arc welding. This operates with a low arc voltage, with the result that the length of the arc is so short that droplets come into direct contact with the weld pool before they have grown too large.

As the droplet transfers, the arc is briefly short-circuited. The current from the power source rises, with the result that the tail of the molten material is pinched off by electromagnetic forces. The spatter associated with short arc welding is caused by this pinch-off effect. The transfer of the droplets also produces the characteristic sizzling sound associated with short arc welding. Operating frequency is in the range 50 – 200 Hz.

Short arc welding is particularly suitable when welding thin sheet metal. With the low rate of heat input, thermally induced stresses and distortion are low. If the welding parameters are correctly set, spatter is not normally troublesome. Argon, containing up to 25 % $CO_2$, is a suitable shielding gas: pure $CO_2$ is also sometimes used.

*Problem areas with short arc welding*

Performance requirements in respect of the power source characteristics are demanding if the welding process is to be successful, and it is sensitive to disturbances. It may be necessary to make fine adjustments to the arc voltage and power source inductance settings in order to obtain optimum characteristics.

At higher current settings, spatter tends to become troublesome. Over about 180 – 200 A, the spatter droplets increase in size and burn fast to the workpiece beside the weld. On the other hand, the low heat input of the method involves a greater risk of poor fusion.

When welding aluminium, the high thermal conductivity of which leads heat rapidly away from the weld, it is difficult to obtain acceptable weld quality with short arc welding.

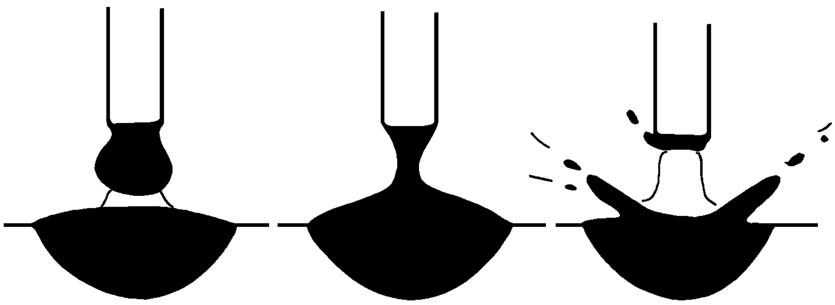


*Figure 1. Droplet transfer with short arc welding.*

## Spray arc welding

Above the critical current limit at which the molten droplets in the arc become small, it is easy to achieve a stable arc without short circuits or spatter. Spray arc welding performs well, both when welding with mixed argon/$CO_2$ or with pure argon. However, the higher the $CO_2$ concentration in the shielding gas, the higher the current has to be before a spray arc can be achieved. Using pure $CO_2$, it is not possible to obtain a spatter-free spray arc at all.

The drawback of spray arc welding is its high thermal input, which means that it is best suited to welding thicker materials and when making horizontal joints.

## Thermal pulsing

Thermal pulsing is generally used with TIG welding in order to achieve improved control over the weld pool. The pulse frequency is in the range 1 – 10 Hz. The process involves heating a point on the workpiece until the metal is completely molten. The welding current is then reduced, such that much of the weld pool solidifies, after which the process is repeated as the arc is moved along the joint.

The pulse current is higher than would normally be used for continuous welding. Supplying heat in this way, at a high rate but for a short time, makes more efficient use of the energy with less thermal conduction of the heat away from the weld. This has a number of benefits:

- Less sensitivity to gap width variations
- Better control of the weld pool during positional welding
- Better control of penetration and the penetration profile
- Reduced sensitivity to varying heat removal
- Reduced size of heat-affected zone (HAZ) in the workpiece material.

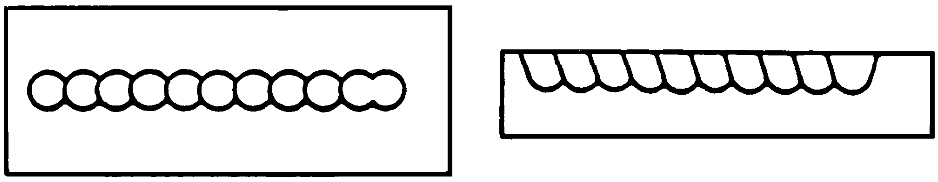


*Figure 2. Thermal pulsing.*

Combining thermal pulsing with short arc welding (sometimes referred to as long pulse welding) makes it possible to weld thinner materials and with a better outflow of the weld metal than would otherwise be possible. Note, however, that the pulse current must be higher than would be the case during continuous welding if optimum results are to be achieved.

## Pulsed arc welding

Pulsed arc welding is used mainly for welding aluminium and stainless steel, although it is also used for welding ordinary carbon steel. The method of controlling the transfer of the droplets by current pulses (30 – 300 Hz) from the power source makes it possible to extend the spray arc range down to low welding data. The process provides a stable and spatter-free arc as a welcome alternative to short arc welding.

The pulses serve two purposes: supplying heat to melt the filler wire, and then also to pinch off just one molten droplet for each pulse. This means that, as the wire feed speed increases, the pulse frequency must also increase. This will have the result of maintaining the droplet volume constant at all times. a low background current contains the arc between the pulses. Although the current amplitude in each pulse is high, the average current – and thus the heat input to the joint – can be kept low.

*Advantages*

- The process is fully controlled and spatter-free.
- The ability to extend spray arc welding down to lower welding data is particularly suitable when welding materials such as stainless steel or aluminium. It becomes possible to weld thin materials, or to perform positional welding, with better results than would be obtained with short arc welding.
- Pulsed arc welding is sometimes used within the normal spray arc range in order to provide better penetration into the material.
- A stable arc can be produced even when using a somewhat thicker filler wire. This is useful when welding aluminium, where it can be difficult to feed the filler wire due to its softness.
- Recent work indicates that the efficient droplet pinch-off reduces overheating of the droplets, resulting in less fume production.

*Disadvantages*

- The production rate is generally lower with this method than with short arc welding. The greater heat input, relative to that of short arc welding, reduces the maximum usable wire feed speed.
- Pulsed arc welding restricts the choice of shielding gases. As with spray arc welding, the $CO_2$ concentration of an argon/$CO_2$ mixture must not be too high: the usual 80/20 % gas mixture, as used for short arc welding, represents the limiting value.

# The welding process

With MIG welding, there is a connection between the welding current and the rate of melting the material. During ordinary non-pulsed welding, this relationship is utilised by setting the required wire feed speed and arc voltage.

The arc voltage affects the arc length, so that a higher arc voltage results in a longer arc.

The wire feed speed determines the welding current, i.e. the current must be such that the filler wire is melted away at the same rate as it is fed forward

## Self-correction of the arc length

The point of intersection of the arc characteristic and the power source load characteristic is referred to as the working point: it corresponds to the particular welding current and voltage at the time. In order to ensure a stable arc length, the slope of the power source characteristic must not be too steep.

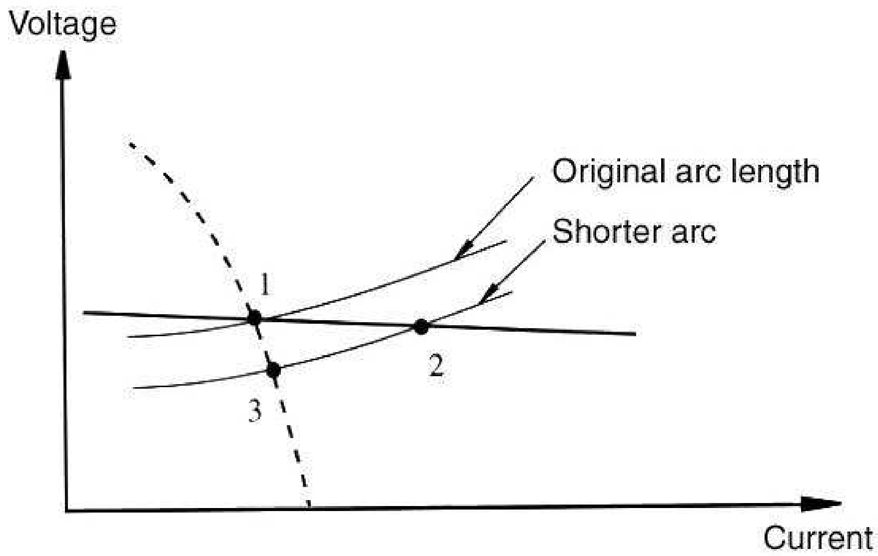



*Figure 3. How the slope of the power source characteristic affects the welding current if the arc length is altered.*

If the arc length is reduced, e.g. as a result of some external influence, the voltage will drop and the current will increase. It can be seen from Figure 3 that, if the slope of the characteristic is slight, the current increases from working point 1 to working point 2, while it will increase only to working point 3 if the slope of the characteristic is steep. The increased current results in a greater rate of melting of the filler wire, so that the arc length is restored. MIG/MAG power sources have a linear characteristic in order to provide good self-correction performance.

The self-correction performance means that the length of the arc is determined by the set voltage. In other words, if the welder lifts the welding torch, it is not the arc length that changes but the filler wire stickout.

It is also the self-correction performance that determines the welding current if a filler wire of a particular diameter is fed forward at a particular wire feed speed. The current adjusts itself so that it is exactly that needed to melt the filler wire at the same rate as it is being fed forward. Changing the voltage, for example, does not significantly alter the current.

### Wire stickout

If the welder raises the welding torch, the length of the filler wire conducting the welding current changes. However, as the wire is thin, and the current is high, it quickly becomes heated: with a long stickout, it can in fact become so hot that it is almost melted simply by the heat produced by its electrical resistance. However, a preheated filler wire upsets the balance of the self-correction process: less current is now needed to melt the filler wire, and so the current automatically adjusts itself to a lower value.

The volt drop across a long stickout reduces the volt drop across the arc itself. If the power source has a somewhat drooping characteristic, this can actually be an advantage as, when the current falls, the voltage increases, which then compensates for the volt drop along the length of the stickout.

## Material transport in the arc

### Electromagnetic forces and plasma jet

Any conductor through which current is flowing is surrounded by a magnetic field. The interaction between the current and the field produces a mechanical force, the direction of which is radially inwards into the conductor. If the conductor is not cylindrical in shape but, for some reason, is increasing or decreasing in diameter, there will also be a longitudinal force component.

As the filler wire melts, it turns into a droplet of metal which, as a result of surface tension, remains hanging at the end of the wire. However, as the welding current is flowing through the droplet, it also is subject to electromagnetic forces. Depending on conditions, these magnetic forces may tend either to detach the droplet from the tip of the wire or to retain it there.

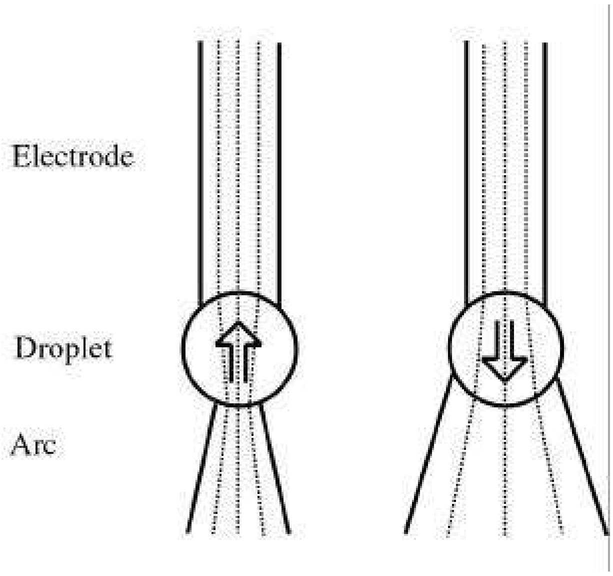



*Figure 4. How the electromagnetic forces act on the droplet depends on the width of the arc in relation to the wire diameter. Note that this diagram is highly schematic.*

If the arc is narrow, the current is concentrated through a small point on its way out through the droplet. As a result, upward-acting forces (see Figure 4) will act on the droplet. This is the case when the welding current is low, or when $CO_2$ is used as the shielding gas. Under these conditions, the droplets can grow and become quite large. The opposite applies when welding with a thin filler wire, an argon-rich shielding gas, high current and high voltage. Under these conditions, the arc is wider than the filler wire, and the current paths expand downwards. The forces acting on the droplet are then directed downwards, producing a downward stream of small droplets of molten material. This produces a stable, short-circuit-free spray arc.

*Critical current limit*

The droplet size reduces with increasing current, although there is a boundary at which the droplets suddenly become much smaller. This boundary is set by the value at which the resulting magnetic force change direction, and is affected by such factors as the filler wire diameter and the composition of the shielding gas. When using pulsed arc welding, the current value in each pulse must be higher than the critical current limit in order to ensure that the metal droplets are pinched off.

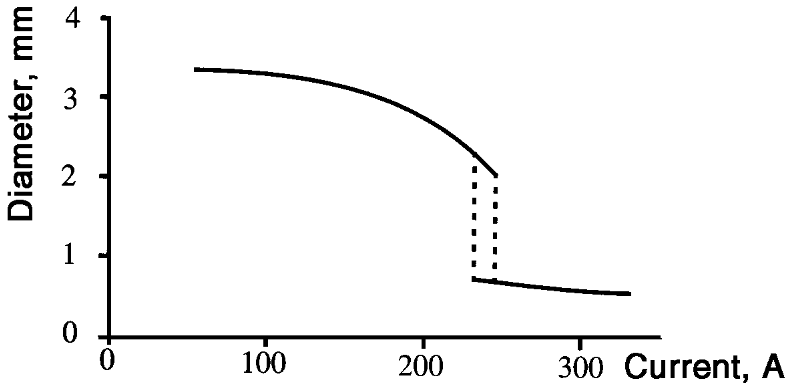



*Figure 5. Above a certain critical value of current, the droplets from the filler wire reduce in size.*

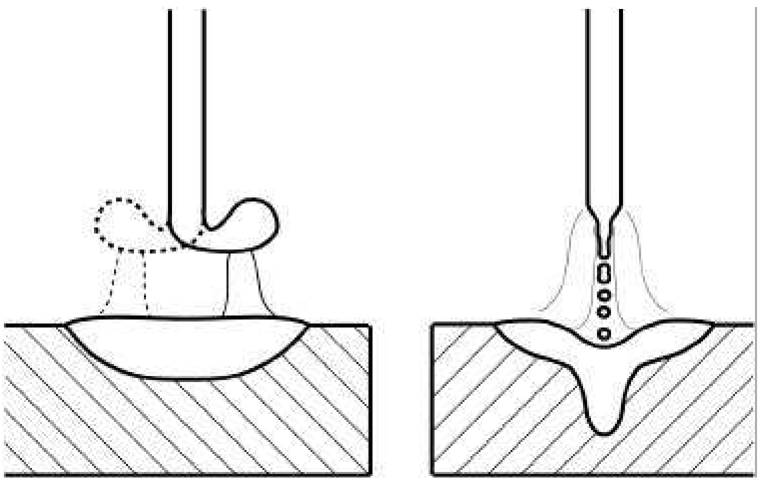


*Figure 6. The droplets are large when welding with $CO_2$ as the shielding gas or with low current values. A stable spray arc is produced when the current rises above the critical current limit value.*

## Short arc welding

A solution to the problem of the large droplets that occur when welding with low currents is to reduce the arc length so much that the droplets contact the weld pool before they have grown too large. Surface tension then quickly transfers them to the weld pool, with the final throat being pinched off by the electromagnetic forces.

As the droplet short-circuits the arc, the arc voltage drops close to zero and the current rises. However, it is important that the current does not rise too much, as this would result in too strong a pinch-off effect, creating considerable noise and producing a lot of spatter. The rate of rise of current is often limited by the incorporation of an inductor in the power source, as shown in Figure 7.

Both the voltage and the inductance need to be adjusted to appropriate values in order to achieve the best performance from short-arc welding. However, there are many other process parameters that also affect the welding performance.

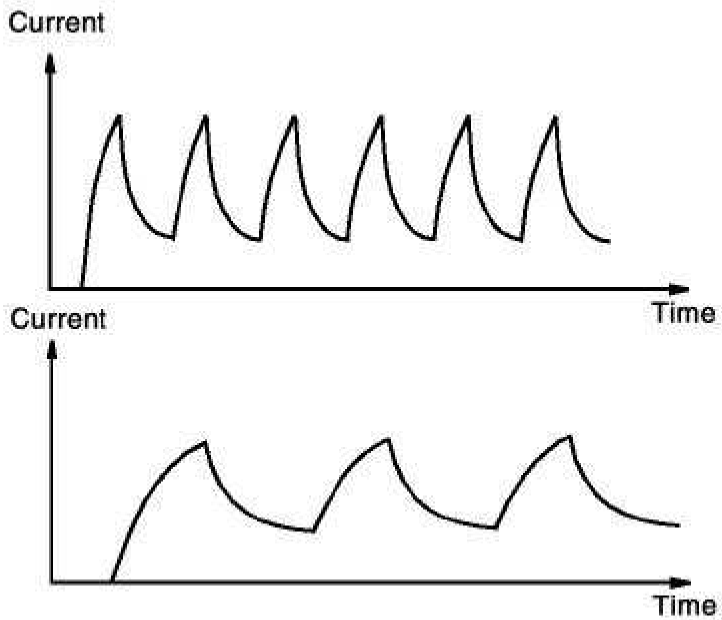



*Figure 7. The effect on the current curve of inductance values for short arc welding. The lower curve is produced by a higher value of inductance. As the current peaks are lower, the quantity of spatter is reduced.*

**Pulsed MIG welding**

The values of the current in the pulses in pulsed arc welding lie above the critical current limit at which the droplets are easily released from the tip of the filler wire. The pulse duration is chosen such that exactly one droplet is pinched off by each pulse. During the time between pulses, the current is low, so that the average current is low, and yet the droplets are transferred as in a spray arc.

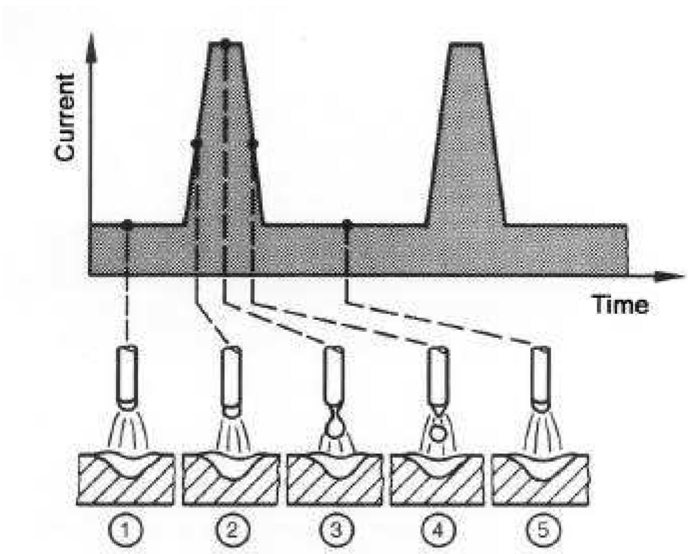



*Figure 8. Each current pulse pinches off one droplet.*

# Pulsed arc with the ARISTO 2000

## Pulse parameters

In principle, the four underlying parameters of pulse current value, background current value, pulse-on time and pulse-off time are required in order to define the pulse parameters. However, in the ARISTO 2000, the pulse-off time has been replaced by the pulse frequency. In addition, the rise and fall flanks of the current pulse can be given a slope, adjustable in nine steps (1 – 9), with each step corresponding to 100 µs. This affects the welding noise. A steep slope produces more noise, at a higher frequency. On the other hand, excessive slope can, in the worst case, affect the ability of the pulse to pinch off the droplet.

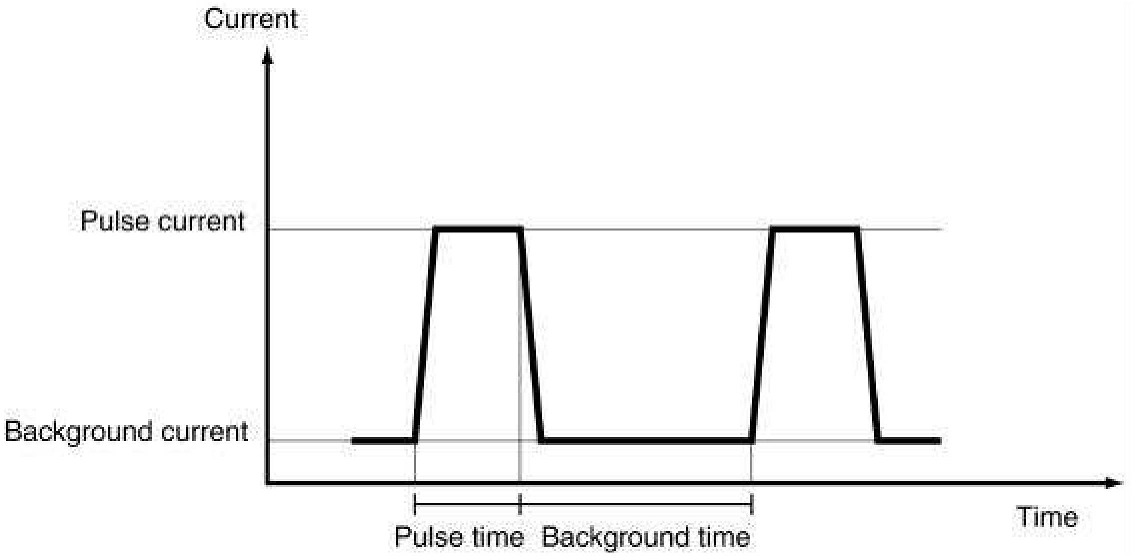



*Figure 9. Naming the pulse parameters.*

## Synergy lines

One of the welding modes supported by the ARISTO 2000 control unit is pulsed MIG/MAG welding. If this is selected, followed by selection of the correct filler wire material, shielding gas and filler wire diameter, the control unit will automatically set the optimum voltage and all pulse parameters that have been tested and selected for this particular combination, and as suited to the wire feed speed that has been set. Changing the wire feed speed automatically adjusts all the other settings. The relationship between the feed speed and the other parameters is referred to as the synergy line. About 150 synergy lines are stored in the database that is programmed into the control unit.

## Basic conditions for correct operation of pulsed arc welding

Two important conditions must be fulfilled if the process is to be stable. One is that the pinch-off force must be that required to pinch off one droplet per pulse, and the other must be that the current is that required to melt the filler wire at the correct rate so that the arc length is maintained constant.

*Pinching off the droplet*

During the current pulse, the droplet is subjected to a downward force, which is used to pinch off the droplet. However, surface tension tends to keep the droplet in contact with the wire. In order to break the droplet away from the wire, the force acting on it must be applied for a sufficient time. Simplified, this can be expressed as:

Force x Pulse time = Constant

i.e. a higher value of pulsed current means that the time can be reduced. The force acting on the droplet is proportional to the square of the current, which means that we can say:

$$I_p^2 \times t = \text{Constant}$$

where $I_p$ = the pulse current. This formula is perhaps not exactly correct, but it does show that the current has a greater effect than does the time.

With all parameters correctly set, the droplet will be pinched off immediately after the pulse ceases, without forming any spatter.

*Melting the filler wire*

It has been explained above that, if the arc length is to regulate itself, the power source must have a constant voltage characteristic. However, this risks conflicting with the requirement of being able to control the pulse parameters at the same time. Ideally, we would like to be able to control both the pulse current and the background current (i.e. constant current control), but this would then put self-correction of the arc length at risk. Different manufacturers of welding equipment have solved this problem in different ways.

One way is to maintain constant voltage of the pulse and a constant value of background current, sometimes referred to as CVCC (Constant Voltage and Constant Current) control. The pulse current will then vary, depending on whether the arc length is long or short.

Another alternative is to do the opposite, i.e. CCCV, which means that it is the background current that is varied.

These operating principles restore control of the arc length, although to some extent at the cost of control of the pulse parameters.

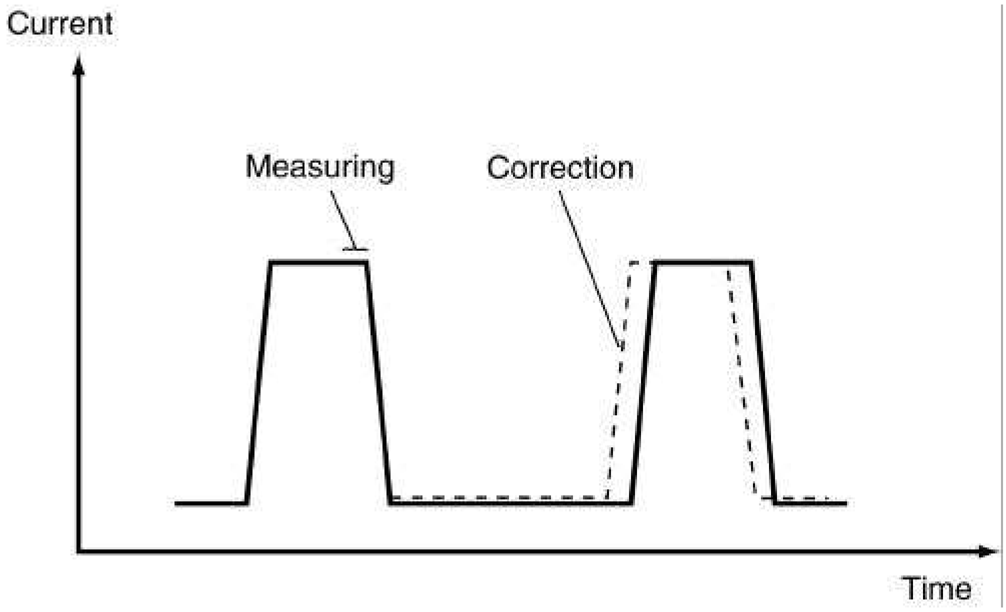



*Figure 10. The arc voltage is measured at the end of the pulse, and the background current duration changed if necessary.*

ESAB has found an interesting solution to the problem, enabling both self-correction and control of the pulse parameters to be used together. This involves a CCCC characteristic, i.e. constant current during both the pulse and the background current period between pulses. The arc voltage is measured at the end of the current pulse, thus providing a signal to indicate the arc length. If the arc is too short, the pulse frequency is increased, which is done in practice by maintaining the pulse width but reducing the background current duration.

Reducing the background current duration also reduces the amount of heat supplied by it. In order to be able still to melt a droplet of the same size, compensation is provided by increasing the value of the background current (see Figure 10). This method of control makes it possible to fulfil the conditions necessary to pinch off each droplet (the pulse current and duration remain the same), while at the same time controlling the arc length.

It is important to have constant current control during the background current period, as this ensures that the arc will not extinguish at the lowest current settings.

## Variations in wire stickout

The welding voltage consists of the volt drop across the arc plus a small volt drop due to the wire stickout. If the stickout increases, then the volt drop across it also increases. If the regulator simply maintained a constant welding voltage, it would mean that the arc voltage would be reduced to below its ideal value, with the resulting risk of short circuits starting to occur.

### Voltage regulator parameters $K_a$ and $K_i$

A voltage regulator with such exact response would, in other words, be a drawback as far as dealing with unintentional variations in wire stickout are concerned. A longer stickout would mean that the total arc voltage tended to increase. A somewhat less efficient regulator, not completely restoring the voltage value, would actually be preferable. However, the optimum setting depends on the actual material of the filler wire - aluminium and stainless steel, for example, have completely different resistivities - and also on the wire thickness. For this reason, both the $K_a$ and $K_i$ regulator parameters are adjustable, and are included in the controlled parameters used for creating synergy lines.

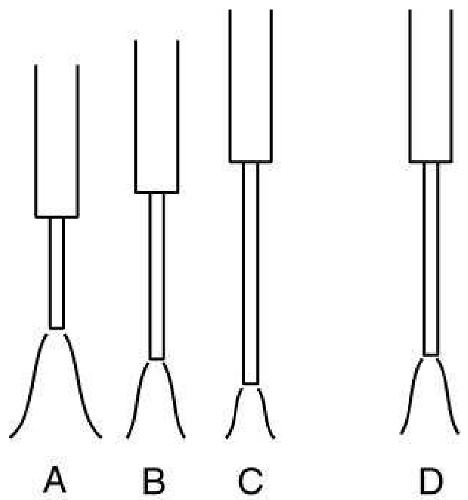



*Figure 11. The effect of stickout length on pulsed arc welding. A, B and C show what happens if the welding voltage is kept constant. D is the more ideal case, in which the voltage is allowed to increase somewhat as the stickout increases.*

$K_a$ is the proportional element, corresponding to the gain of the regulator. a low value means that the voltage is not maintained constant quite as exactly.

$K_i$ is the integrating function that attempts to reduce the error over a longer period. Here, too, a low value produces less exact regulator performance.

Values of $K_a$ and $K_i$ are expressed as percentages.

## The DSC-function

DSC - Drop Short-circuit Correction - is a function that helps the welder achieve more exact control of the arc length. Setting the correct arc voltage is particularly important when welding aluminium. It is often desirable to set an arc voltage that is only just high enough to produce an almost short-circuit free spray arc. The DSC function operates during pulsed arc welding, to make the voltage regulator respond to short circuits by slightly increasing the voltage. If the short circuits stop, the regulator reverts to its normal control mode and reduces the arc voltage back towards the set value. In practice, this means that if the voltage has been set slightly low, the DSC function will automatically increase it by the necessary amount. To some extent, this produces what is known as an adaptive arc, i.e. one that sets itself to the correct voltage value.

### Short circuit handling

If the arc is short-circuited by molten droplets during pulsed arc welding, there is a risk that the short circuit will tend to continue. During normal short arc welding, an almost constant voltage characteristic is used, which means that short-circuit currents increase until the short circuit is interrupted. Pulsed arc welding uses constant current control, which means that, in principle, there would be no reaction at all to a short circuit.

Short circuit handling means that, as soon as a short circuit occurs, it is identified by the regulator which then temporarily changes the characteristic over to short arc control, which is optimised to deal with short circuits.

## Crater filling

As long as welding is in progress, the surface of the weld pool is heated from the top by the arc. This means that as the weld pool solidifies, it does so in the direction from the sides and bottom of the joint up towards the surface. If the arc should suddenly be extinguished, the direction of solidification changes slightly so that it is more parallel with the workpiece. Inclusions and contaminants become trapped in the weld metal where the solidification fronts meet in the centre of the joint, and are not driven to the surface. Stresses due to contraction as the material cools can cause a crack or crater in the weld metal.

(When welding in steel, it is elements such as carbon and sulphur that reduce the melting point of the iron. As the material solidifies, these elements become concentrated into the last part of the weld to solidify.)

One way of dealing with this problem is to reduce the welding current slowly at the end of the weld. When using pulsed arc welding, this reduction takes place over about 1 – 1.5 s. If short arc welding, with some degree of spatter, can be accepted, the voltage can be dropped more rapidly, reducing the time for crater filling to only about 0.5 – 0.8 s.

The controlled parameters for crater filling are time and final wire feed speed. If the operator departs from the synergy characteristic, it is necessary also to decide upon a suitable final voltage.

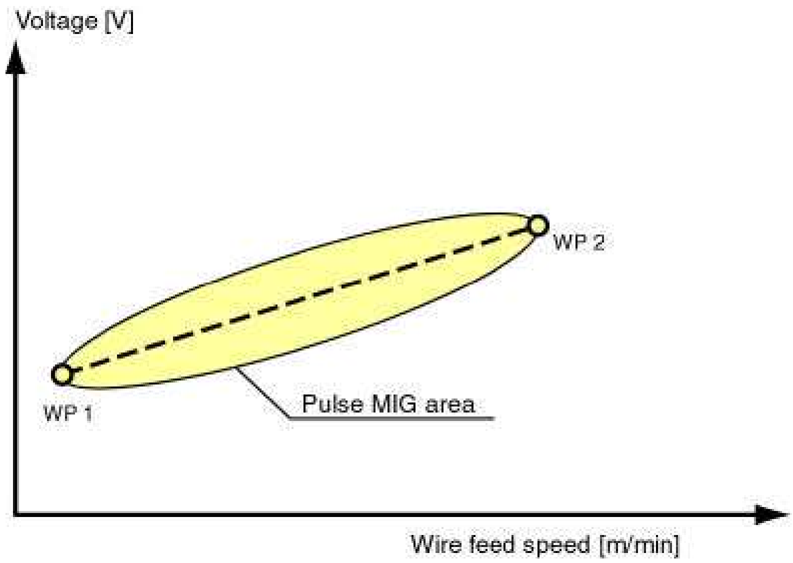



Figure *12. A synergy line can be created by plotting the pulse parameters at two points.*

## Creating custom synergy lines for pulsed arc welding

The ARISTO 2000 allows the user to create his/her own synergy lines. This is done by trying out welding data for the particular weld at two different wire feed speeds. When satisfactory conditions have been achieved, the two sets of welding data are then saved in two memory positions.

The following points are helpful when testing out pulsed arc welding parameters.

1. Start from a synergy line that is thought to be closest to the new synergy line.
2. In order to prevent the arc length regulator from interfering with the tests, set constants $K_a$ = 0 and $K_i$ = 0.
3. Set wire feed speed to 3 – 4 m/min (or to the lowest desired speed).
4. Watch the arc length when welding: it is affected by the pulse amplitude, the background current, the pulse duration and pulse frequency. Adjust these parameters to give a suitable arc length. If short circuits occur, this is a sign of too short an arc length. When a suitable arc length has been arrived at, check the voltage in the MEASUREMENT display during welding, to produce a starting value of arc voltage. Having done this, set $K_a$ = 6 – 5 % and $K_i$ = 0 – 3 %. The voltage regulator has now been brought into operation, and will attempt to maintain the set voltage. It may be necessary further to adjust the voltage.
5. If it is difficult to maintain a sufficiently high linear welding speed, it may help to increase the pulse frequency. Compensate for this by reducing the pulse amplitude or the background current to give the right arc length. (The background current should not be reduced to below 24 A, in order to leave room for the voltage regulator to operate.) Do not reduce the pulse amplitude so much that the 'pressure' in the arc disappears.
6. If the energy in the pulse is insufficient, i.e. if the pulse amplitude is too low and/or the pulse time is too short, the droplets will not be pinched off by each pulse. This will reveal itself as a flickering arc, with large droplets and

short circuits, and with considerable amount of spatter ending up outside the weld.

7. Having found the correct settings for this low wire feed speed, save them in the first memory position and then repeat the procedure for more advanced welding data. Save the results in the second memory position. Give a name to the synergy line and then command the programme to produce a set of synergy data.

**General advice**

When setting the pulse frequency, a basic guide is to assume that each droplet is about the same size as the wire diameter. Thus, for example, with a wire feed speed of 6 m/min (100 mm/s) and a wire diameter of 1 mm, 100 Hz is a suitable frequency from which to start.

As mentioned above, the controls also provide an adjustable ramp for the rise and fall slopes of the current pulse in order to reduce welding noise. The less steep flank gives a quieter weld. Nine steps of adjustment are available: in general, the longest time can usually be accepted without having too much effect on the ability of the pulse to pinch off the droplet.

If the slope of the flank is too steep, there is also a risk of supplying the arc length regulator with incorrect measured value signals. It could be seen from Figure 10 that the voltage is measured at the end of the pulse time: this is because it is important that it should be measured when the current is constant. However, as a result of the inductance of the welding cables, there is an inductive voltage component as the value of the current changes. This manifests itself as a voltage detected by the measuring circuit, but which does not exist across the arc. If the regulator is to work properly, the voltage must be measured during constant current, and the current must also have been constant immediately before the measurement is made.

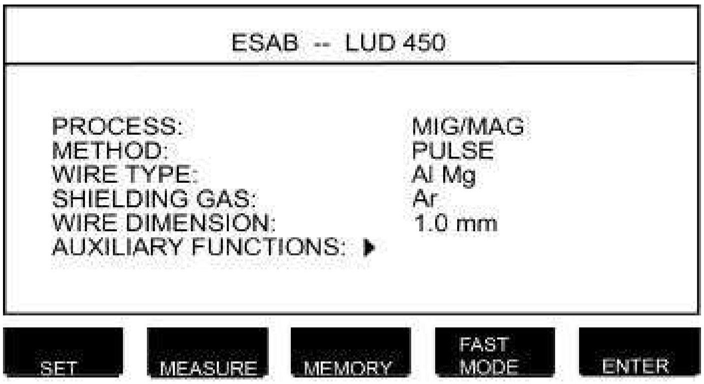
## The length of the welding cables

The inductance of the welding cables constitutes a limitation of the speed at which the current can be changed. As a general recommendation, the length of cable between the power source and the wire feed unit should not exceed 8 m. If the length is increased beyond this value, there is a risk of the rate of rise of current becoming too slow for some welding requirements. The regulator in the power source attempts to increase the voltage as much as needed to eliminate the error between the actual value and set value signals. If the error has not been eliminated when the arc voltage is measured at the end of the pulse, the measured value will be too high and the arc length controller will be disengaged. (Although there is a separate wire for measuring the voltage at the welding torch, this does not help as the inductive voltage drop in the welding cable is picked up by the signal cable as a result of the good magnetic linkage between them.)

## The control unit

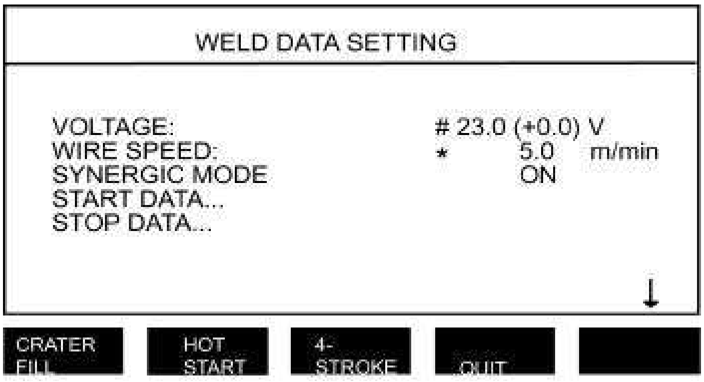
The following is a brief description of how to use the PUA 1 control unit when making your own synergy lines.

- Press the MENU button.



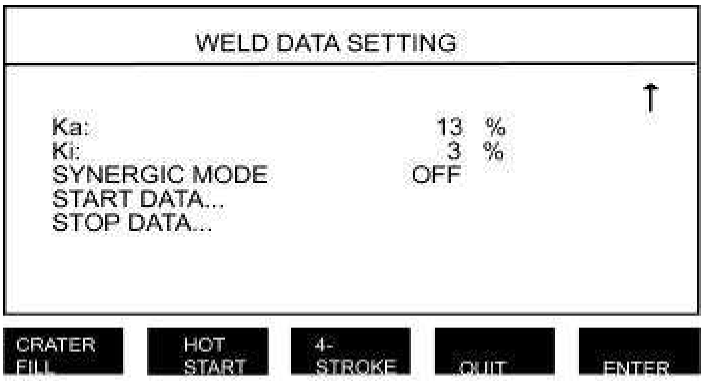

Select data that is as close as possible to the particular weld concerned.

- Press the SET function key.



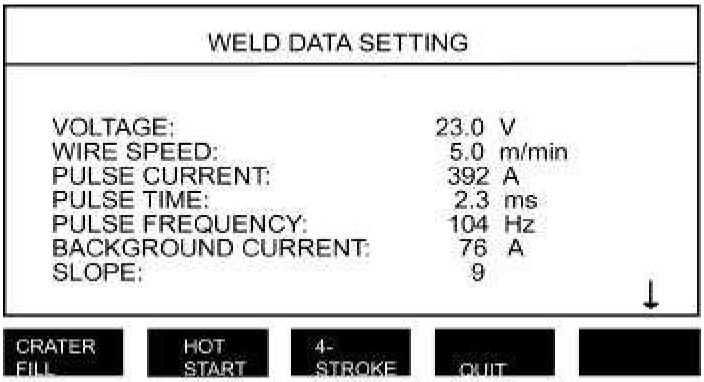

Select a wire feed speed at the lowest setting required.

- Set SYNERGIC MODE to the OFF position.




Disengage the arc length regulator by setting constants $K_a$ = 0 and $K_i$ = 0.

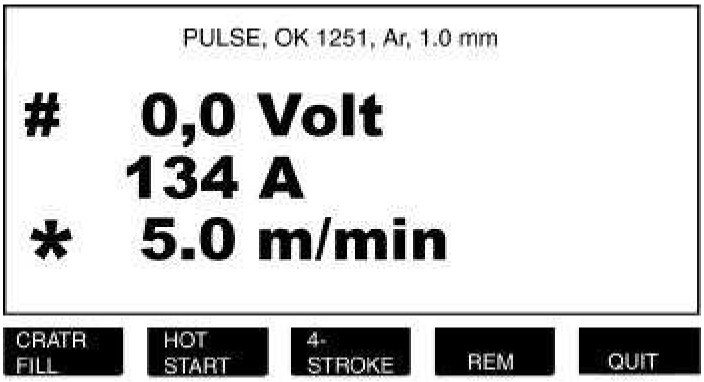
Using the arrow keys, move the cursor up to the upper display.




Adjust the pulse current, pulse time and pulse frequency as needed. Make sure that a satisfactory arc length is obtained.

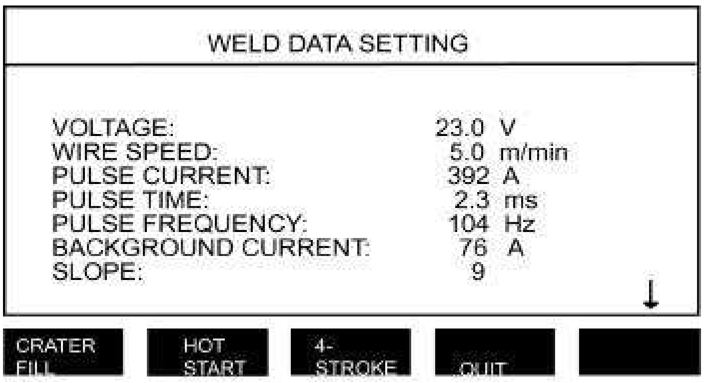
Check the welding voltage by bringing up the parameter values display.

Press QUIT and then MEASURE.




Read the voltage.

Go to MENU, SET.

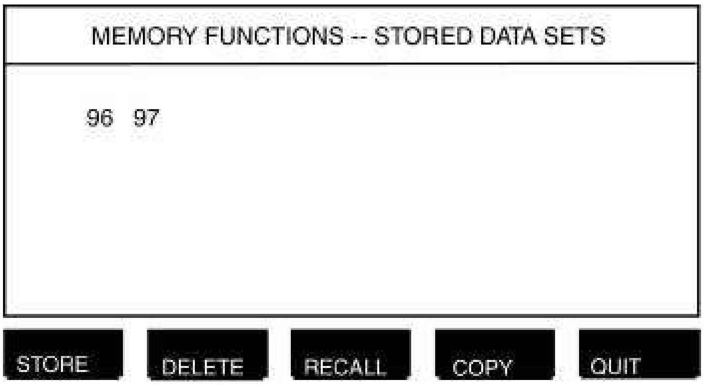



Enter the voltage value.

Adjust $K_a$ and $K_i$.

Make a test weld and, if necessary, adjust the voltage.

Go to MENU, MEMORY.




Select STORE and store the welding data at position 96.

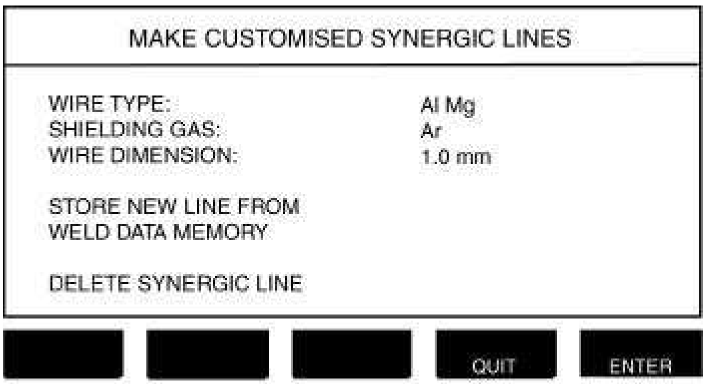
Repeat the settings for a new working point with high welding data.

*Note:*

- that the pulsed time, the slope, $K_a$ and $K_i$ settings must be the same as were used for the low welding data settings, *and*
- that other values must be higher.

Store the results under memory position 97.

Go to MENU, AUXILIARY FUNCTIONS, USER DEFINED SYNERGIC DATA.




Enter WIRE TYPE, SHIELDING GAS AND WIRE DIMENSION.

*Note* that you cannot save the same values as already exist. Choose a new name for at least one of the details.

Select STORE NEW LINE and press ENTER.