

Figure 4.64: Welding process profile for different travel speeds 0.2 ms before short circuiting event in wire 2 (single configuration)

Regarding the amount of metal displaced by the arc in the case of the trailing wire in general, it was smaller than in the case of the leading wire (Figure 4.65). Probably this is related to the fact that the arc is pointed forwards, not in the direction of the concentration of molten metal as in the case of the leading wire. However, it is expected that the trailing arc reduces the stability index of the leading arc in the tandem configuration case, where there will be concentration of molten metal also in the front of the trailing arc, which, being pushed forwards, will make the pool more unstable also under the leading wire. The stability of the process in tandem configuration is likely to be deteriorated considering that there will be no synchronisation between the short circuiting events taking place on both wires, which might let the weld pool with ‘more freedom’ to achieve arbitrary patterns of oscillation.

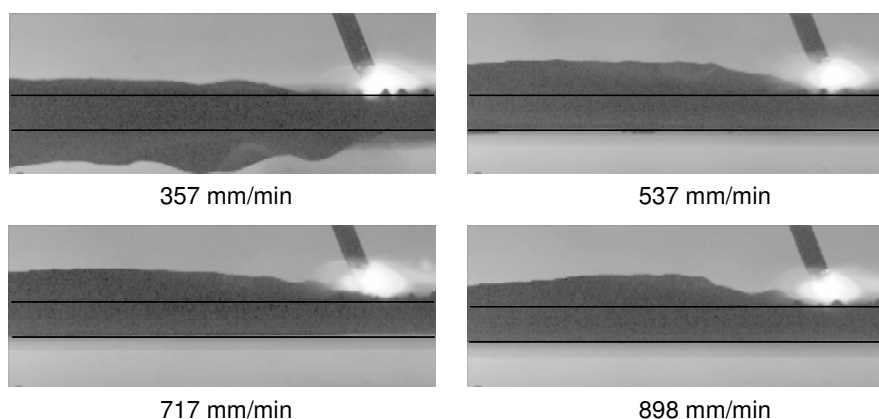


Figure 4.65: Welding process profile for different travel speeds 4 ms after start of pulse in wire 2 (single configuration)

4.4.3 Using wire 1 and wire 2 in tandem configuration

Table 4.20 shows the travel speed levels used and the results for the stability index, voltage and current for the leading wire (wire 1) in tandem configuration. Figure 4.66 shows the relationship between welding travel speed and stability index achieved for this wire. Despite the fact of the standard deviation was very high for all levels of travel speed tried, a similar tendency to that found when using the leading wire on its own seemed to be present (the stability index decreased as the travel speed was increased).

Table 4.20: Stability index, voltage and current for wire 1 (tandem wire configuration)

WTS (mm/min)	Mean Stability Index	Stability Index Standard Deviation	Mean Current (A)	Mean Voltage (V)
808	0.59	0.0678	109.3	16.30
988	0.54	0.0764	112.4	16.29
1168	0.49	0.0862	112.8	16.04

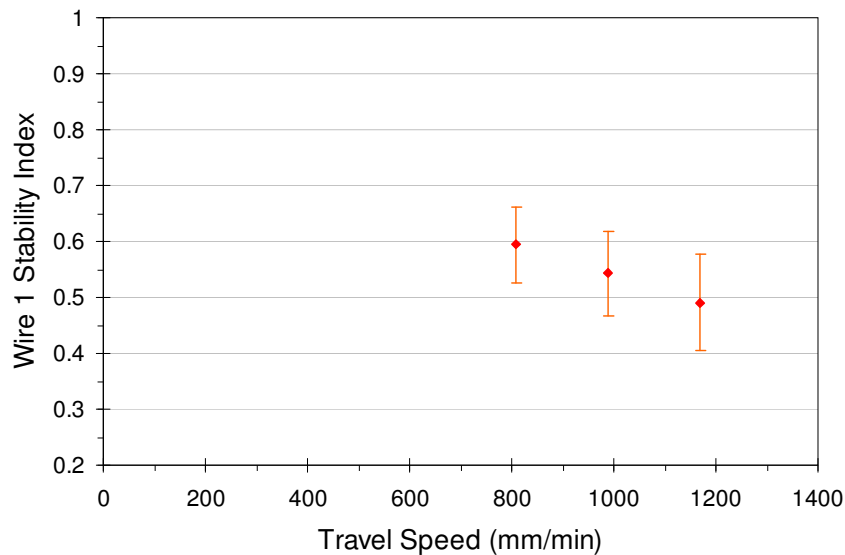


Figure 4.66: Relationship between welding travel speed and stability index for wire 1 (tandem wire configuration)

Table 4.21 shows the travel speed levels used and the results for the stability index, voltage and current for the trailing wire (wire 2) in tandem arrangement whilst Figure 4.67 shows the relationship between welding travel speed and stability index achieved for this wire. As it happened for the leading wire, the standard deviation was significantly high. Regardless of this fact, a similar tendency to that identified for the first 3 levels of travel speed when the trailing wire was used by itself seemed to occur. The highest stability index was achieved for the lowest travel speed (full penetration), followed by a sharp decrease and a subsequent rise as the travel speed was increased.

Table 4.21: Stability index, voltage and current for wire 2 (tandem wire configuration)

WTS (mm/min)	Mean Stability Index	Stability Index Standard Deviation	Mean Current (A)	Mean Voltage (V)
808	0.64	0.0398	112.7	17.11
988	0.43	0.1059	112.1	18.03
1168	0.46	0.0601	115.8	17.70

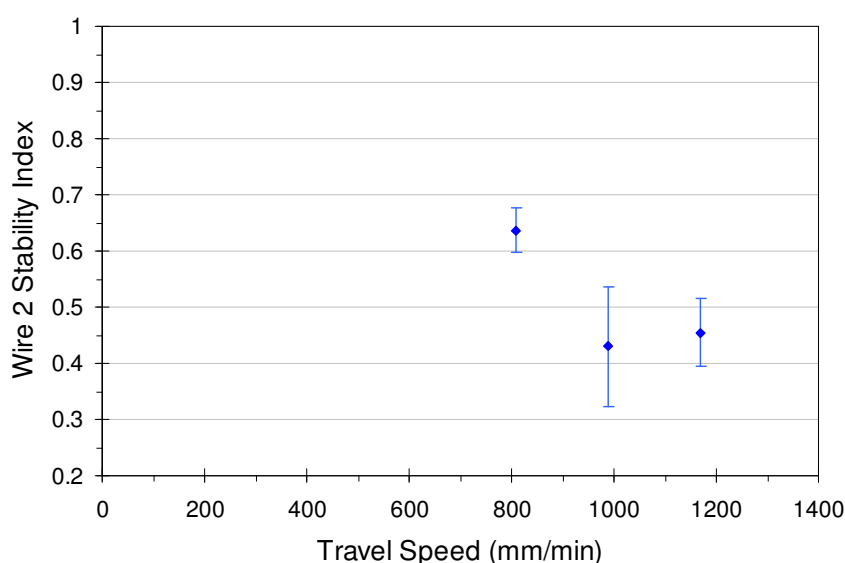


Figure 4.67: Relationship between welding travel speed and stability index for wire 2 (tandem wire configuration)

The high standard deviation in the stability index found when using both wires under the controlled short circuit mode can be explained by the freedom that the process has to be in any state of the short circuiting at any time. This fact leads to a random oscillation of the weld pool mostly due to the pulse of current applied after the short circuit rupture. Figures 4.68 to 4.71 show a sample of transient electrical data with reference to a chart of synchronised images (frames) presented by Figure 4.72. As a matter of illustration on how random the process can be, in a given moment both arcs may be in short circuiting (frame c) or in open arc state (frame f) or one of the arcs may be in short circuiting and the other in open arc state (frames h and t). The pulses of current after the short circuiting events, as expected from the results of tests using one of the wires at a time, induced large displacement of molten metal. As the pressure exerted by each arc over the weld pool induces molten metal movement in opposite directions a remarkable concentration of mass was established between the wires. It is worth mentioning that this accumulation of material can also happen in the case of tandem pulsed GMAW, but without having any major effect since it does not touch the droplets at the tips of the wires (the pulse state is not affected by the weld pool). However, with the controlled short circuit mode there is no synchronisation between the control applied to the arcs, and the instant of sort circuit in each wire may be very dependent on the oscillation of the weld pool. As a consequence, all states of the control (including the moment that the pulse of current is applied) can be affected.

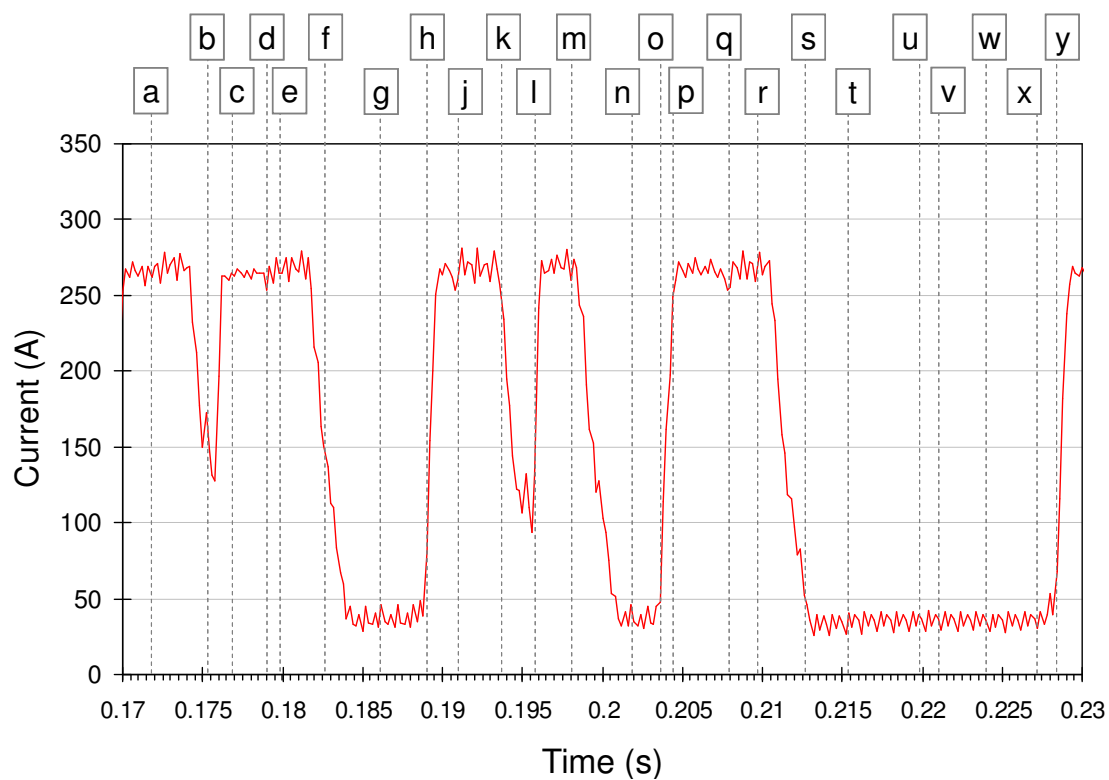


Figure 4.68: Leading wire transient current with index for chart of images (Figure 4.72)

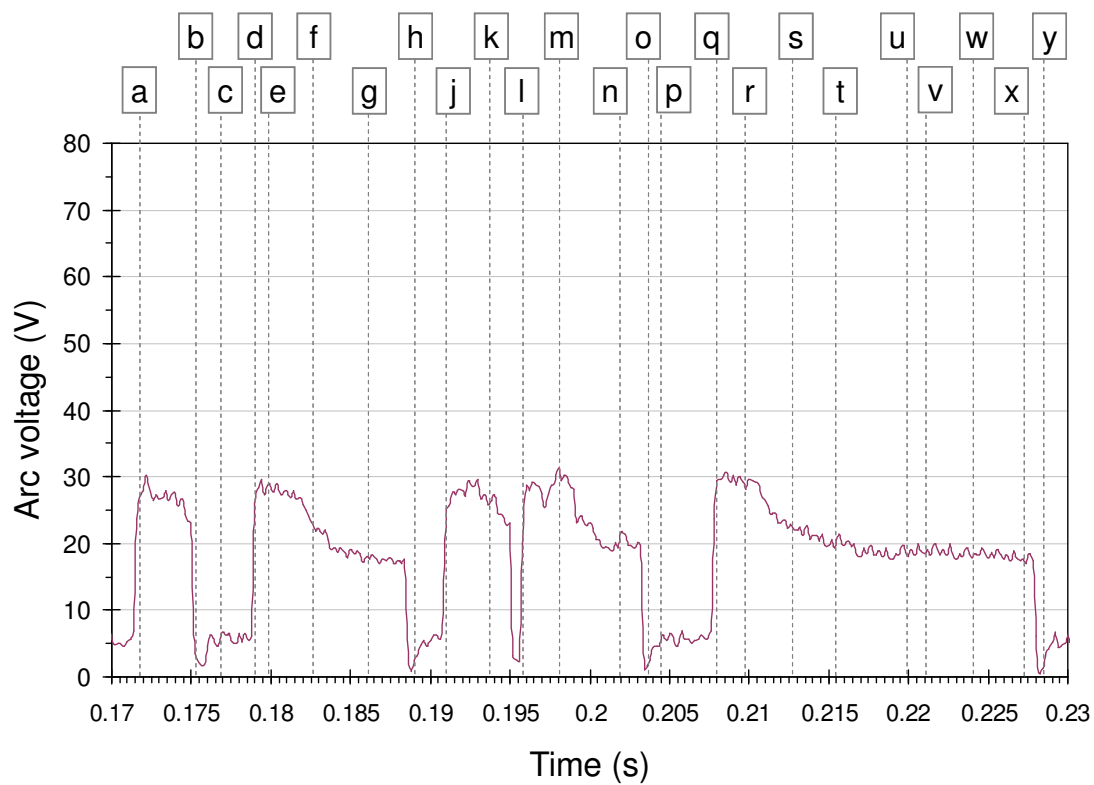


Figure 4.69: Leading wire transient voltage with index for chart of images (Figure 4.72)

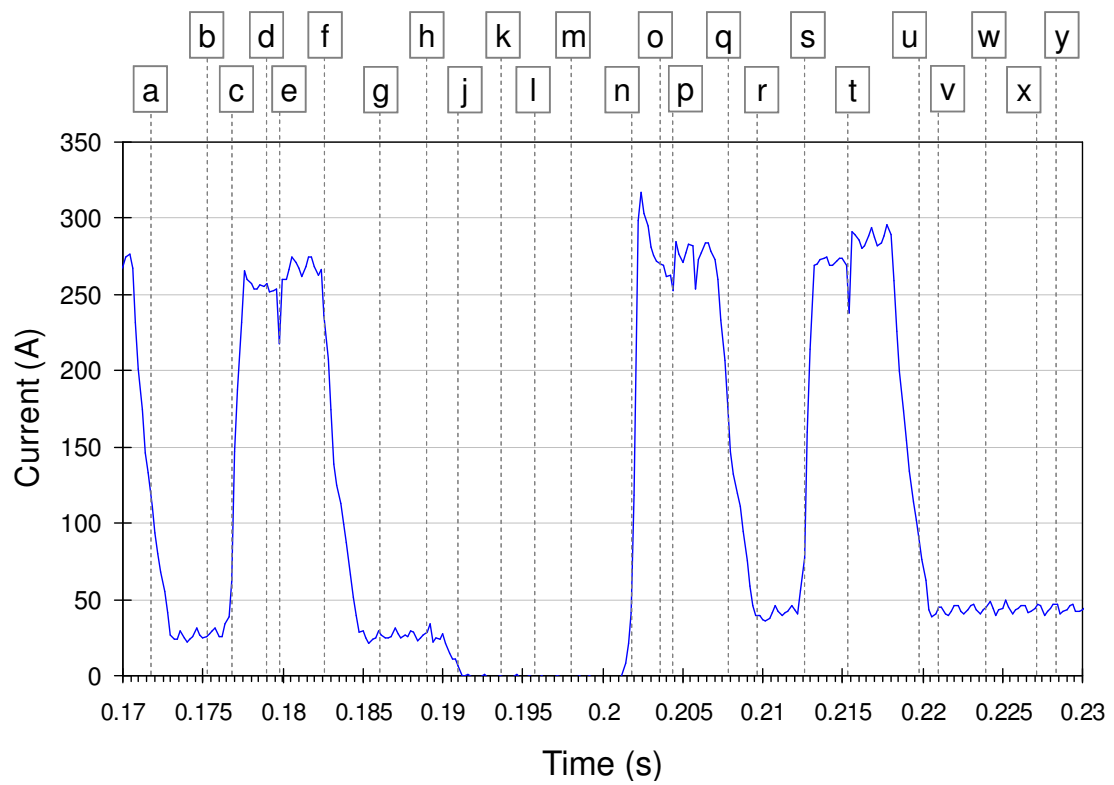


Figure 4.70: Trailing wire transient current with index for chart of images (Figure 4.72)

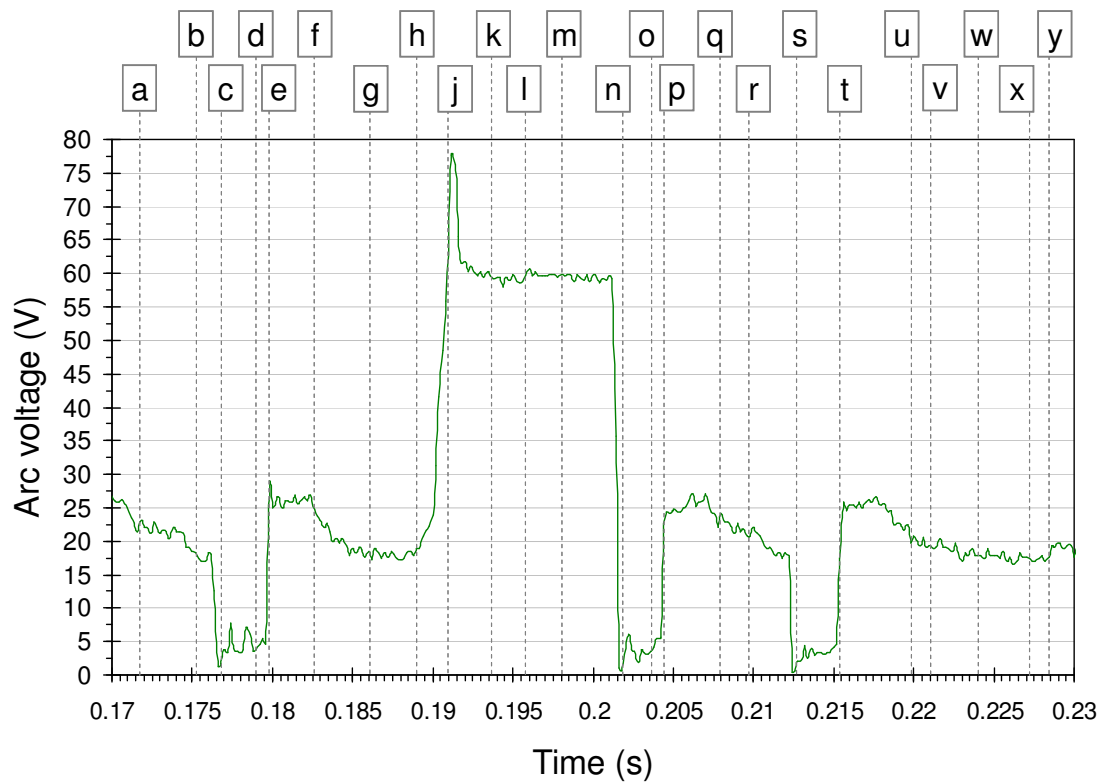


Figure 4.71: Trailing wire voltage transient with index for chart of images (Figure 4.72)



Figure 4.72: Chart of images with index for Figures 4.68, 4.69, 4.70 and 4.71

As illustrated by Figure 4.73, this inter-dependence between the process state and the weld pool (mass of accumulated molten metal) oscillation leads to a kind of “snow ball” effect, which makes the process very unstable as expressed by the stability index measurements. It is worth saying that the process presents some short moments of stability for both wires, but this stability is soon broken in one of the wires by the oscillation of the molten metal mass between them. Subsequently the molten metal is affected by the instability and can easily affect the other wire, which is also affecting the molten metal. Even

the short circuiting duration can be directly affected by the movement of the mass of molten metal. As it is shown in Figure 4.72 frames d, e, p and q, sometimes the metal bridge moment of rupture is affected by the movement of the molten metal away from the initial region of contact between the droplet at the tip of the wire and the weld pool. The arcs are also under the risk of being attracted by each other when arcs co-exist in both wires, with the deviation in the trailing arc being remarkably higher (frame r). This fact tends to be in accordance to Scotti et al. (2006) who observed that the trailing arc is more deviated than the leading one when using pulsed mode. This attraction can even culminate in arc interruptions as shown by frames j (trailing arc interruption) to q (reestablishment of trailing arc after short circuiting (frame n)). These interruptions are another fact that contributes to the degree of instability in the process, since they change the concentration of molten metal between the wires and, consequently, the weld pool oscillation behaviour. As it happened for the pulsed mode case, the arc interruptions were observed to be a fault more likely to occur in the trailing wire and the situation favouring these faults - leading arc at high current levels and trailing one at low levels - is present. The difference is that now the arc can be quickly re-established after the next short circuit. As there is no synchronisation between the current applied to the wires, any attempt to suppress these interruptions via software control is impracticable. One possibility to deal with this problem would be by using one of the wires in controlled short circuit mode and one in pulsed mode. This would make one of the wires “poll oscillation proof” regarding the metal transfer and by this approach some synchronisation could be implemented via process control software.

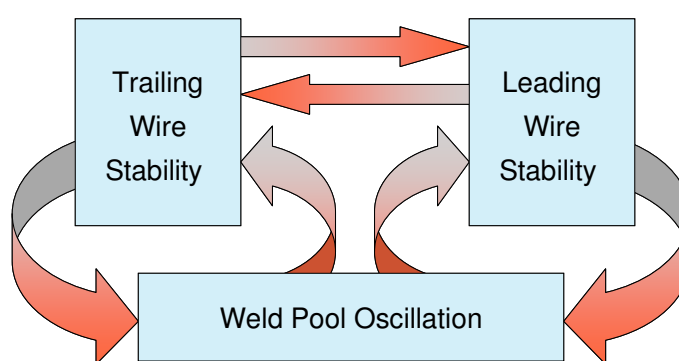


Figure 4.73: Multiple inter-dependence between leading and trailing wire stability and weld pool oscillation in tandem GMAW using controlled short circuit in both wires

Another observation can be done when comparing the “weldable” travel speed range for single and tandem wires. Regardless of allowing operations at higher travel speeds (without humping formation) than the single wire approaches, it seems that the tandem arrangement shorted the operational range of the process. In other words the gain in

maximum travel speed was not as high as expected and usually happens when moving from single to two wires arrangement. From visual observation during the tests and from the resulting bead visual aspects, it seems that as the travel speed was increased the trailing arc started to oscillate its length resulting in a bead as shown in Figure 4.74. A hypothetical explanation for this fact is that as the travel speed was increased the weld pool started to cool down (consequence of less heat being added to the plate) and the trailing arc started to hit over “cold” metal, which led to arc length variation and wavy bead aspect. Considering this hypothesis, one solution for this problem would be by making the weld pool “hotter” by decreasing the inter-wire distance or by adding an extra heat source between the wires, like a Laser beam, for instance. Another possibility is that humping was the cause of the trailing arc length variation and resulting bead aspect. Further tests would be needed to investigate this fact. Figure 4.75 shows the typical visual aspect of weld beads inside the operational range for single and tandem wires arrangements. Qualitatively considering the amount of spatters produced, the option using the leading wire singly was the best situation and the trailing wire singly the worse, with the tandem option sitting in the middle.

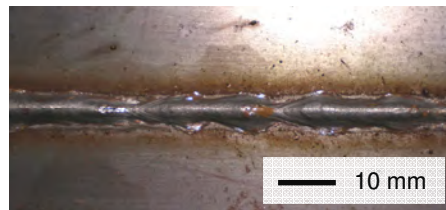
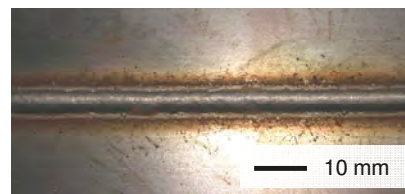


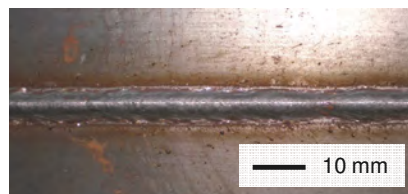
Figure 4.74: Bead aspect when using the tandem wire approach at the top of the travel speed operational range



Trailing wire single



Leading wire single



Tandem wires

Figure 4.75: Typical aspect of weld beads inside the travel speed operational range for single and tandem GMAW arrangements

4.4.4 General comments

The initial tests with tandem GMAW with both wires operating in a controlled short circuit mode showed that the process is highly unstable since there is an intense interaction between the arcs and the weld pool. This interaction led to low stability indexes for both wires and trailing arc interruptions. In view of these facts three main possibilities are considered:

- Using one of the wires in controlled short circuit mode and one in pulsed mode. This would make one of the wires 'pool oscillation proof' regarding the metal transfer and by this approach some synchronisation could be implemented via software control;
- Using an extra source of heat (Laser beam, for example) between the wires allowing to increase the inter-wire distance which may help to make the concentration of molten metal lower and less influent on the short-circuiting period. The fact of adding more heat to weld pool can also increase the operational travel speed range of the process;
- Decreasing the inter-wire distance as a way to increase the operational travel speed range of the process.

4.5 Tandem GMAW with Controlled Short-Circuit and Pulsed Waveform

In order to allow the combination of controlled short-circuit GMAW and pulsed GMAW as a tandem process, a control program (TandemOptPulse - Version 1) was built based on the previous two programs. The new program was built also in order to offer an amicable user interface.

4.5.1 Introduction

This program uses two operational modes of GMAW. The wire number 1 (leading) is set to operate in controlled short-circuit mode and the wire number 2 (trailing) set for pulsed mode. A description of the control developed for pulsed mode in wire 2 is presented in section 4.1 (FlexTandem - Pulsed 1 program). The technique used to control the short-circuit transfer in wire number 1 is presented in section 4.3 (TandemOptarc - Version 1 program). The program combining the pulsed and controlled short-circuit modes was firstly developed to run the wires independently (parallel control without any synchronisation), working as a basis for further development.

4.5.2 Description

In the first version of this control program the current in both wires is controlled independently, that is, there is no dependence between the wires or any kind of synchronisation and the controls for the wires run in parallel. The state diagrams for each wire, and respective descriptions, can be seen in sections 4.1 (pulsed control diagram) and section 4.3 (controlled short-circuit control diagram). Figure 4.76 illustrates the welding current reference waveform and a typical resultant voltage waveform for wire 1 for a normal operating condition where a reduced number of welding states are encountered in the welding cycle (details of the current waveform for all possible welding states are encountered in the section 4.3). Figure 4.77 illustrates the welding current reference waveform for wire 2. Tables 4.22, 4.23, 4.24 and 4.25 list all parameters that can be set in the TandemOptPulse - Version 1 program and present a summarized description of their purpose.

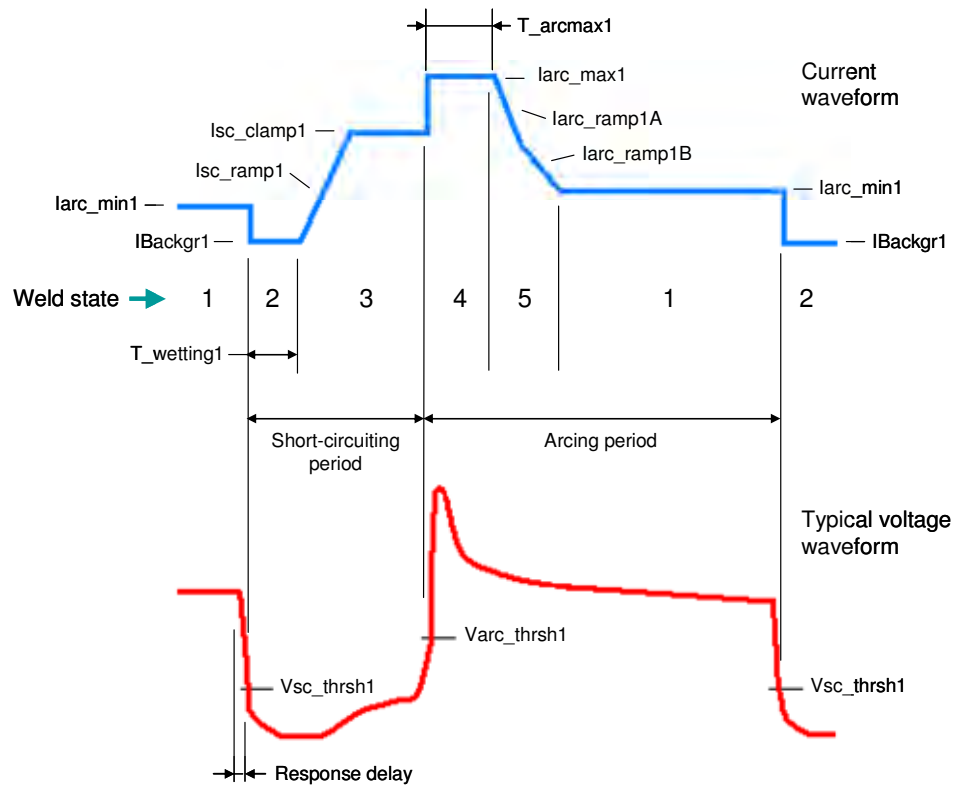


Figure 4.76: Scheme of current and voltage waveforms generated by the TandemOptPulse program for wire 1 for normal process operation

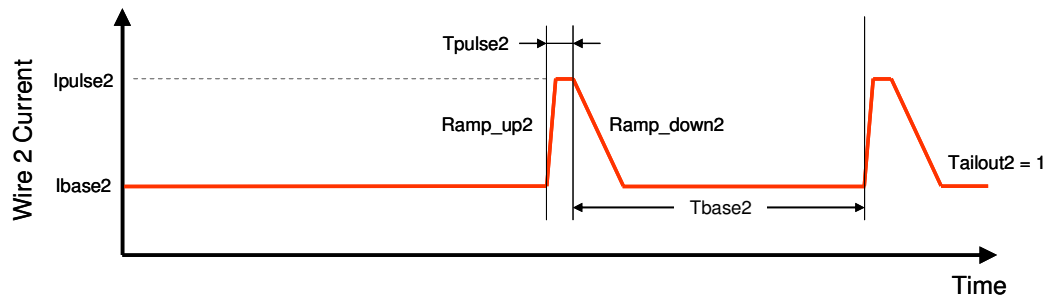


Figure 4.77: Scheme of generic current waveforms generated by the TandemOptPulse program for wire 2

Table 4.22: List of parameters for wire 1 in the TandemOptPulse program

Parameter [units]	Summarized description and/or purpose
Welding parameters	
Isc_ramp1 [A/ms]	Current rising rate during short circuiting in wire 1
Isc_Clamp1 [A]	Short-circuit clamp current level for wire 1
SC_Timeout1 [ms]	Maximum time allowed for wire 1 in short-circuiting state
Isc_max1 [A]	Maximum current allowed for short circuiting in wire 1
Iarc_max1 [A]	Maximum current (pulse) applied when wire 1 returns to arc state
T_arcmax1 [ms]	Time applying Iarc_max1
Iarc_ramp1A [A/ms]	Initial current decreasing rate from Iarc_max1 current level
Iarc_ramp1B [A/ms]	Final current decreasing rate from Iarc_max1 current level
Iarc_min1 [A]	Low current value applied to wire 1 during the arc state
Arc_Timeout1 [ms]	Maximum time allowed for wire 1 in arc state
IBackgr_arc1 [A]	Minimum current applied to wire 1 in case of excessive arc state period
IBackgr1 [A]	Current applied to wire 1 in detection of a short-circuiting event
T_wetting1 [ms]	Time applying IBackgr1 (wetting-in time for wire 1)
Vsc_thrsh1 [Volts]	Short-circuit detection threshold voltage for wire 1
Varc_thrsh1 [Volts]	Arc initiation detection threshold voltage for wire 1
WFR1 [m/min]	Feeding rate for wire 1

Table 4.23: List of parameters for wire 2 in the TandemOptPulse program

Parameter [units]	Summarized description and/or purpose
Welding parameters	
Ipulse2 [A]	Pulse current setting for wire 2
Tpulse2 [s]	Time that wire 2 operates in the pulse current level
Ibase2 [A]	Base current setting for wire 2
Tbase2 [s]	Time that wire 2 operates in the base current level
Ramp_up2 [A/ms]	Rate that the current in the wire 2 goes from the base to the pulse level
Ramp_down2 [A/ms]	Rate that the current in the wire 2 goes from the pulse to the base level
Tailout2 [dimensionless]	Factor that controls the current waveform during the ramp down in wire 2
WFR2 [m/min]	Feeding rate for wire 2
Arc voltage control parameters	
AVC_Ref2 [V]	Arc voltage control reference for wire 2
AVC_Gain2 [A/V]	Arc voltage control proportional gain for wire 2
AVC_Range2 [A]	Arc voltage control adjustment range for wire 2

Table 4.24: Parameters common to both wires in the TandemOptPulse program

Parameter [units]	Summarized description and/or purpose
General parameters	
WFR_creep [m/min]	Creep wire feed rate
Delay* [ms]	Time-shifting between the pulses of wire 1 and 2

* There is no synchronisation between the wires in the first version of the program but the Delay variable was already created thinking on a possible approach to synchronise the arcs.

Table 4.25: Parameters for short-circuit clearance in wire 2 in the TandemOptPulse program

Parameter [units]	Summarized description and/or purpose
Short-circuit clearance parameters	
Isc_max [A]	Clamping short-circuit current
Isc_ramp [A/ms]	Short-circuit ramp-up rate
T_wetting [ms]	Short-circuit wetting time
T_rupture [ms]	Short-circuit rupture time
I_backgr [A]	Background current / background arcing current
Vsc_threshold [V]	Short-circuit detection voltage
Varc_threshold [V]	Arc re-ignition detection voltage
Vneck_det [V]	Short-circuit necking detection voltage

Both previous programs were used as a basis to build the first and basic version of the TandemOptPulse program. The TandemOptPulse - Version 1 interface was based on the FlexTandem - Pulsed 1 and on the TandemOptarc - Version 1 interfaces, basically featuring the same facilities for data loading and saving, parameters setting, etc. Figure 4.78 shows the TandemOptPulse interface/screen. Besides of having an amicable user interface (all parameters can be seen in one screen only, the setting of parameters is facilitated, etc), this program allows setting wire 1 in controlled short-circuit transfer and wire 2 in pulsed mode, resulting in a new approach for tandem GMAW. Examples of parameters file and data logging file used in the TandemOptPulse program are showed in Appendix 5. The DSP program (control program), which is loaded to the system using the interface, was based on the DSP files for the FlexTandem - Pulsed 1 and for the TandemOptarc - Version 1 programs.

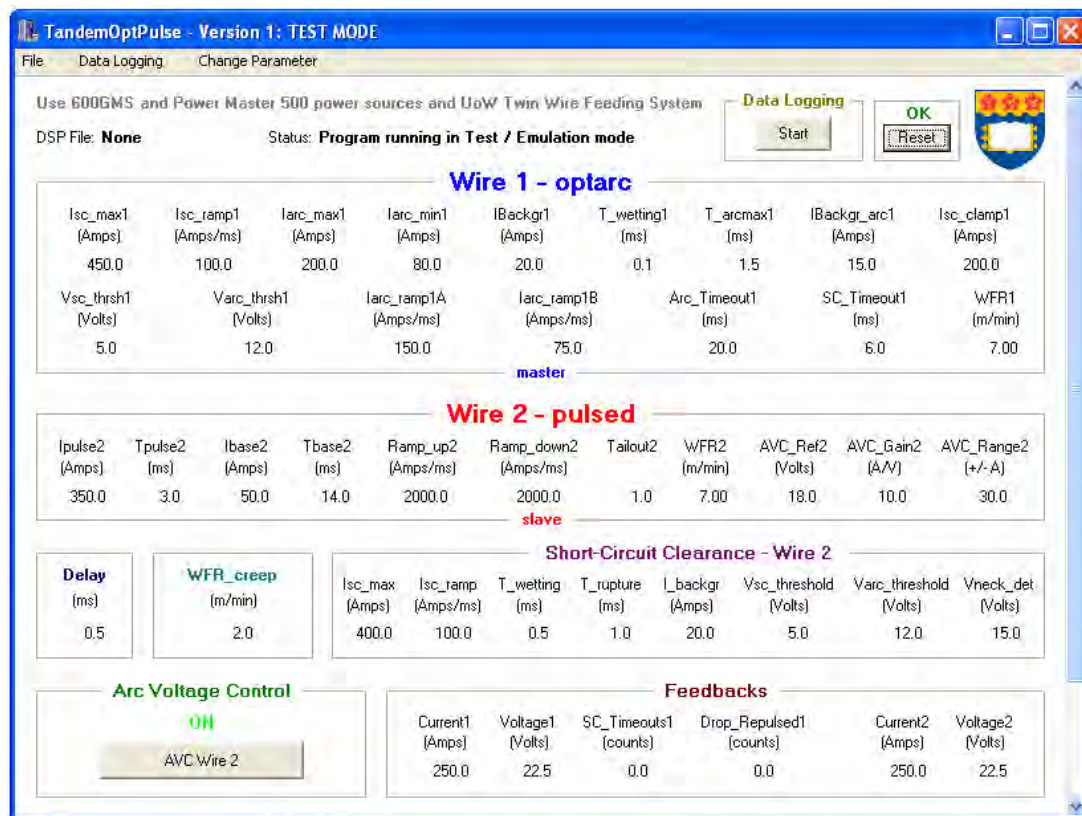


Figure 4.78: TandemOptPulse program screen

Electrical feedbacks

In order to allow the user to carry out a real time checking of the current and voltage values and also some extra information, a group of feedback values is provided in the TandemOptPulse program (Figure 4.79). It is possible to check the instantaneous values of current and voltage for both wires, the number of occasions the process expires the maximum short-circuiting time (SC_Timeouts1) in wire 1 and if any droplet repulsion occurs (Drop_Repulsed1) in wire 1. The methodology behind these feedbacks is described in the section 4.3. The reset button showed previously by Figure 4.78 resets the SC_Timeouts1 and the Drop_Repulsed1 values to zero, which must be done before each weld to avoid considering the events of the previous weld. The current and voltage feedback values are saved in the DSP Logged Data (option in the File menu) to allow detailed analysis (three extra variables can be chosen to be saved in the same file).

Feedbacks					
Current1 (Amps)	Voltage1 (Volts)	SC_Timeouts1 (counts)	Drop_Repulsed1 (counts)	Current2 (Amps)	Voltage2 (Volts)
250.0	22.5	0.0	0.0	250.0	22.5

Figure 4.79: Feedbacks values provided by the TandemOptPulse program

4.5.3 First trials using the TandemOptPulse1 program

In order to verify the program performance, some previous tests were carried out using wave generators to simulate the power sources and an oscilloscope to observe the electrical current signals generated by the program. As this procedure demonstrated that the program was working correctly, some welding trials were carried out. A reasonable combination of parameters was selected (Tables 4.26, 4.27 and 4.28) and data acquisition system was used to record the current and voltage signals for both wires. The shielding gas used was selected in favour of the short-circuit welding mode. Figure 4.80 shows the angle between wires and the way the inter-wire distance and CTWD parameters were considered. Figures 4.81 and 4.92 show the typical current and voltage transient signals. Despite the fact that the program worked from the control point of view (verified by using the oscilloscope and also by intervals of electrical transient from the power sources) the welding process demonstrated great instability in the trailing wire (pulsed mode). As shown in detail by Figure 4.83, 4.84 and 4.85, the trailing arc was recurrently extinguished. It is worth saying that both wires worked without any problem when operated independently (single wire mode by realising one of the wires in the respective wire feeder) using the same welding parameters as for the tandem tests (Figures 4.86, 4.87 and 4.88).

Table 4.26: Parameters selected for wire 1 in the TandemOptPulse program

Parameter [units]	Value
Isc_ramp1 [A/ms]	300
Isc_Clamp1 [A]	250
SC_Timeout1 [ms]	6
Isc_max1 [A]	400
Iarc_max1 [A]	270
T_arcmax1 [ms]	2.5
Iarc_ramp1A [A/ms]	150
Iarc_ramp1B [A/ms]	75
Iarc_min1 [A]	30
Arc_Timeout1 [ms]	20
IBackgr_arc1 [A]	15
IBackgr1 [A]	20
T_wetting1 [ms]	0.1
Vsc_thrsh1 [Volts]	5
Varc_thrsh1 [Volts]	20
WFR1 [m/min]	3.5

Table 4.27: Parameters selected for wire 2 in the TandemOptPulse program

Parameter [units]	Value
Ipulse2 [A]	350
Tpulse2 [s]	2
Ibase2 [A]	50
Tbase2 [s]	16
Ramp_up2 [A/ms]	2000
Ramp_down2 [A/ms]	2000
Tailout2 [dimensionless]	45
WFR2 [m/min]	3.5
AVC_Ref2 [V]	18
AVC_Gain2 [A/V]	5
AVC_Range2 [A]	15

Table 4.28: Welding parameters selected for wire 1 and 2 in the TandemOptPulse program

Parameter [units]	Value
Inter-wire distance	10
CTWD for Wire 1 (mm)	12
CTWD for Wire 2 (mm)	18
Shielding Gas [81.25% Ar + 16% CO ₂ + 2.75% O ₂] (l/min)	35
WTS (mm/min)	985

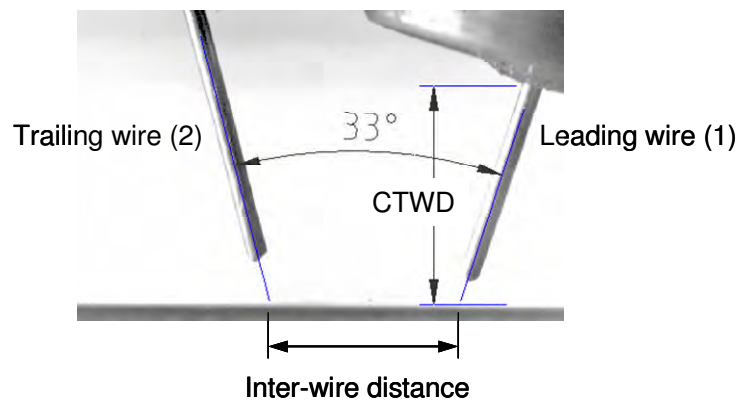


Figure 4.80: Angle between wires, inter-wire distance and CTWD parameters

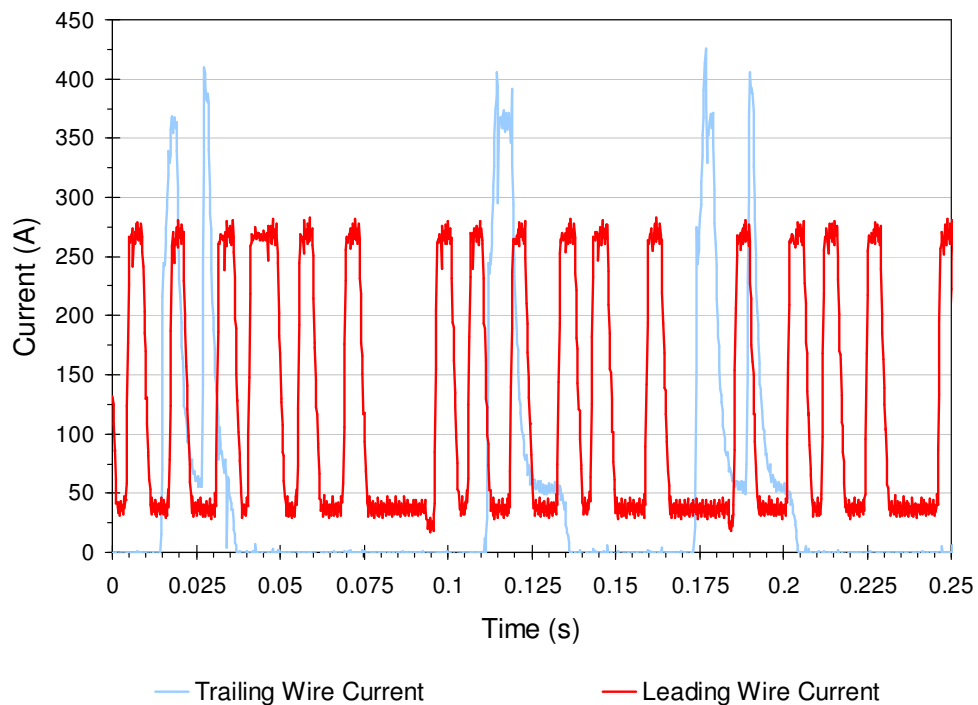


Figure 4.81: Current signals (correspondent to Figure 4.82) provided by TandemOptPulse program (both wires operating) (stability index for wire 1 around 0.60)

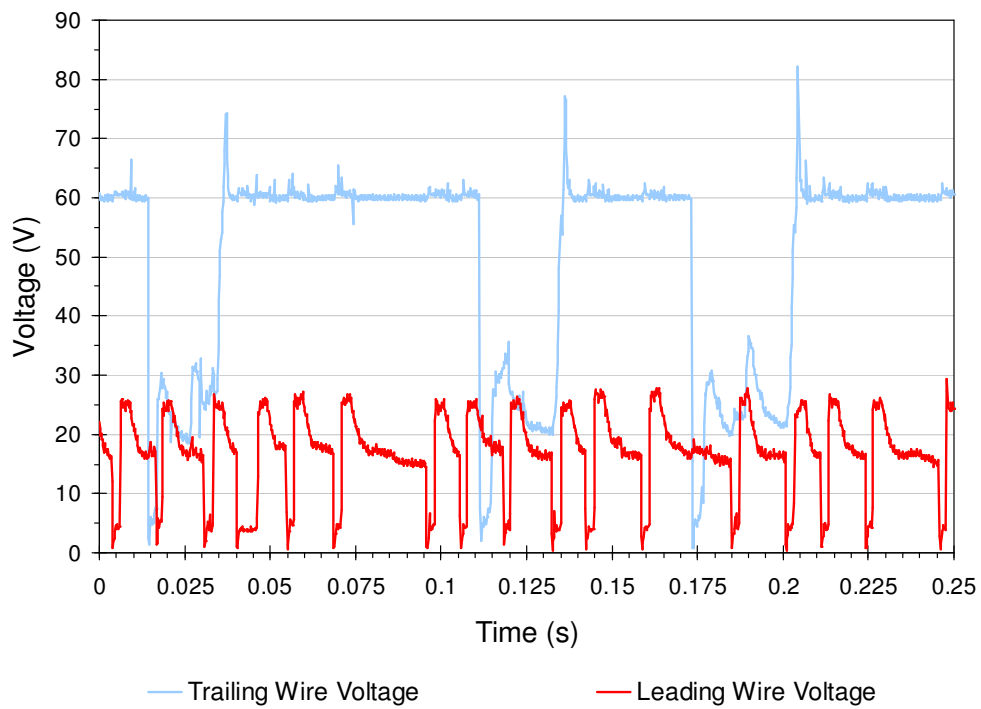


Figure 4.82: Voltage signals (correspondent to Figure 4.81) provided by TandemOptPulse program (both wires operating) (stability index for wire 1 around 0.60)

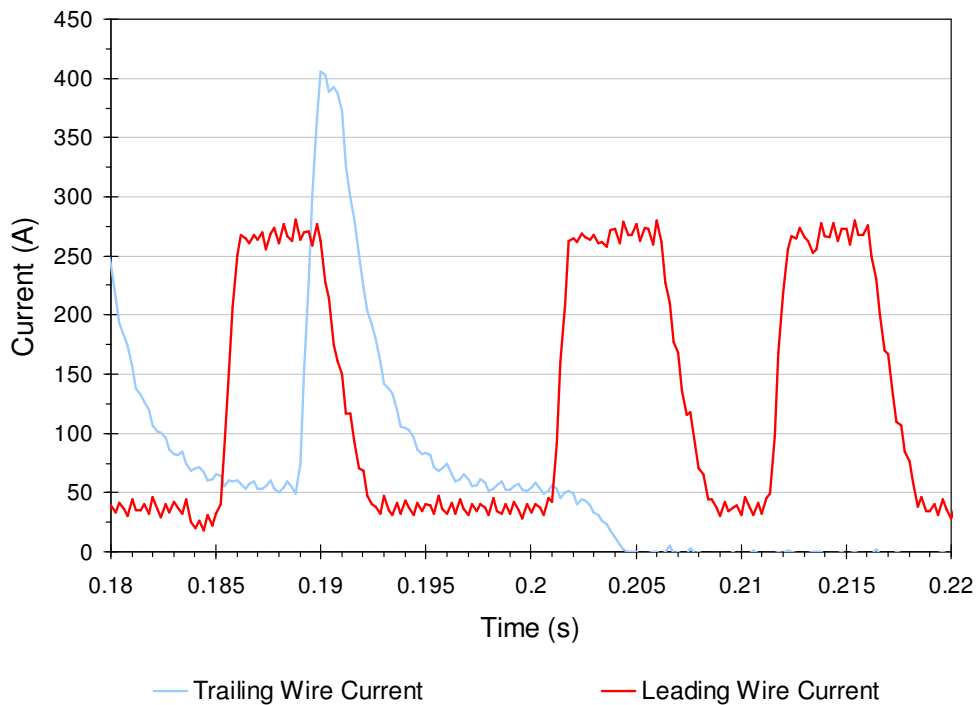


Figure 4.83: Detail of current signals (correspondent to Figure 4.84) during interruption in the trailing arc

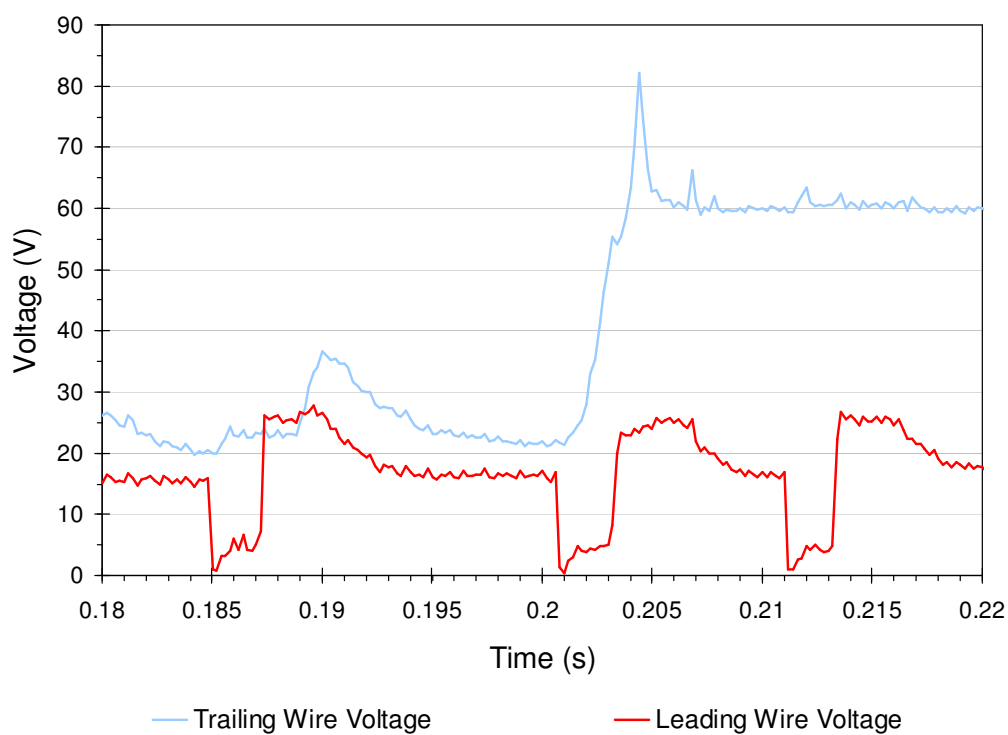


Figure 4.84: Detail of voltage signals (correspondent to Figure 4.83) during interruption in the trailing arc



Figure 4.85: Weld bead aspect produced by TandemOptPulse program (no synchronisation between the wires)

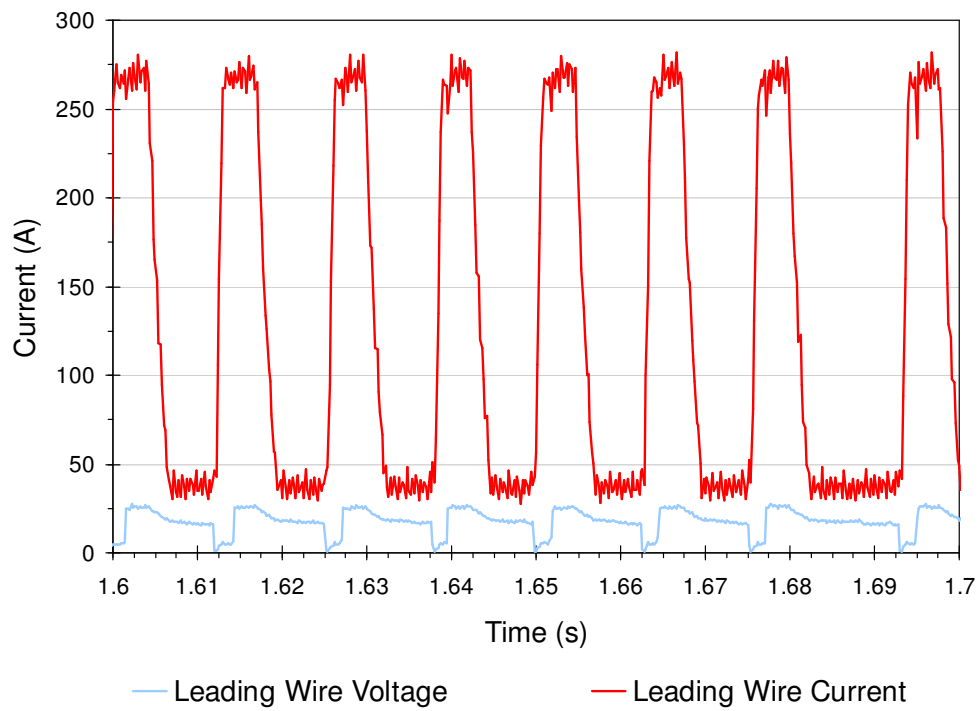


Figure 4.86: Current and voltage signals with leading wire in operation only (controlled short-circuit mode) (stability index for wire 1 around 0.80)

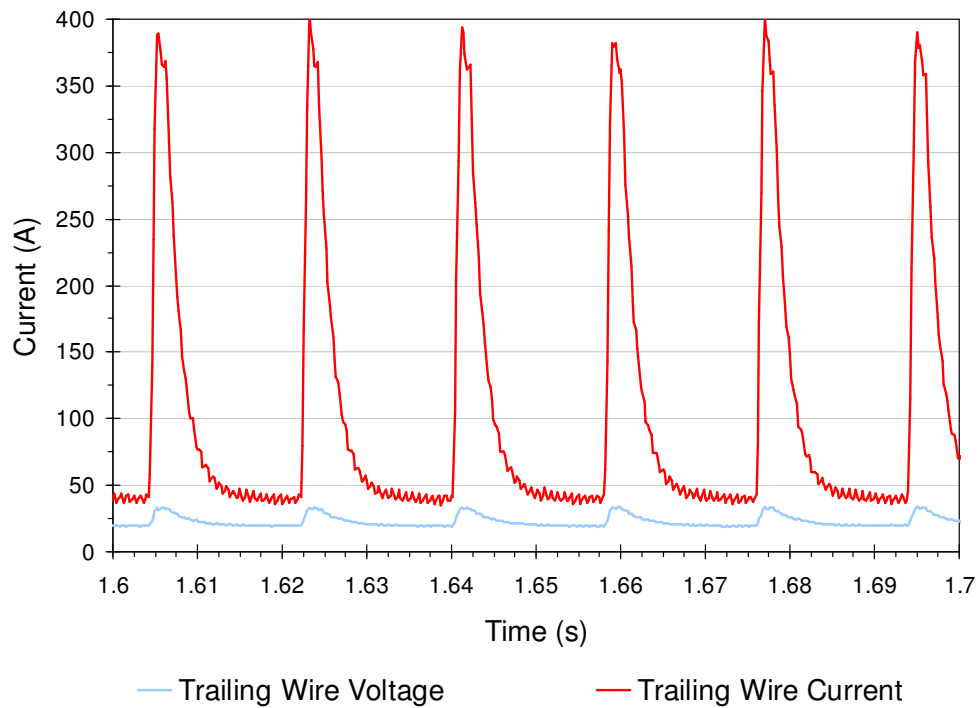


Figure 4.87: Current and voltage signals with trailing wire in operation only (pulsed mode)

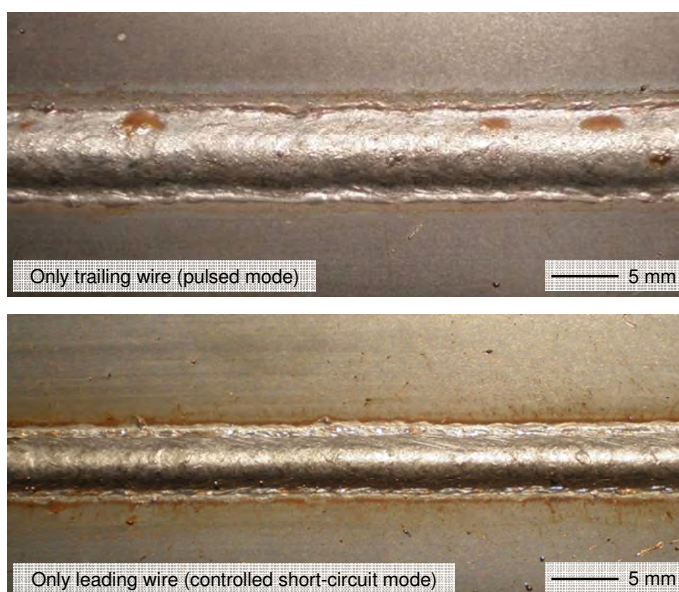


Figure 4.88: Weld bead aspect produced by TandemOptPulse program
(single wire operations)

The situation of having high current in the leading wire and low current in the trailing wire has been a constant mark present when the interruptions occur and it showed to be present in the interruptions observed in the trailing wire for this tandem GMAW approach. Based on the fact that the same problem took place when using pulsed mode in both wires and that in that case the solution was the use of a very small delay between the current pulses applied to the wires ('almost-in-phase' pulses), some modifications were made in the DSP control program to deal with the position of the pulse of current in the trailing wire in relation to the "pulse" of current in the leading wire. From the current level point of view, the current waveform for the controlled short-circuit transfer technique used can be considered as a pulsed wave (cycle of low current and high current).

The first modification in the control program was made to synchronise the pulse of the trailing wire (pulsed mode) to a moment after the beginning of state 4 (pulse of current after end of short circuiting) in the controlled short-circuit process (a delay could be selected in the interface to change the moment of the pulse of current in the trailing wire). In this case the pulsed current waveform was defined by the pulse current level, pulse current time, base current level (all set through the interface) and the frequency of short circuiting of the leading wire (every time the leading wire changed from short-circuiting to arcing period, the base current time in the trailing wire was ended by applying the pulse of current). Figure 4.89 illustrates the resultant synchronisation.

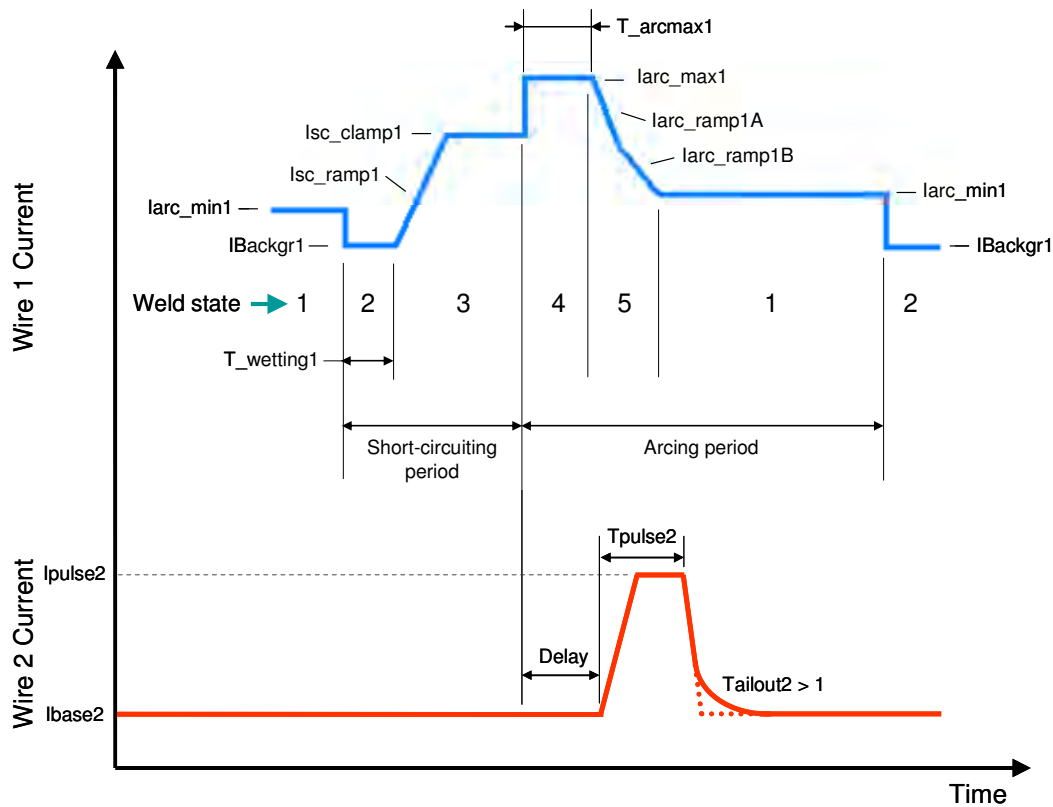


Figure 4.89: Pulse of current applied in the trailing wire a moment after the beginning of state 4 in the controlled short-circuit process

Despite the fact of having a frequency of short circuiting with a mean period of approximately 16 ms (stability index around 0.60), which is close to a period of 18 ms used with success for pulsed GMAW independently and even in tandem pulsed GMAW, this modification was unable to avoid the interruptions. The interruptions may be still taking place due to the fact that the pulse is being applied after the rise in the current level during the short circuiting (even if there is no arc in the leading wire the level of current is high and so the magnetic field affecting the trailing arc, which is still in low level of current). In other words, the pulse of current in the trailing wire may be being applied too late (Figure 4.90). The fact of having the pulses of current applied in the trailing wire too late leads to the scenario favourable to interruptions (high current in the leading wire and low current in the trailing wire).

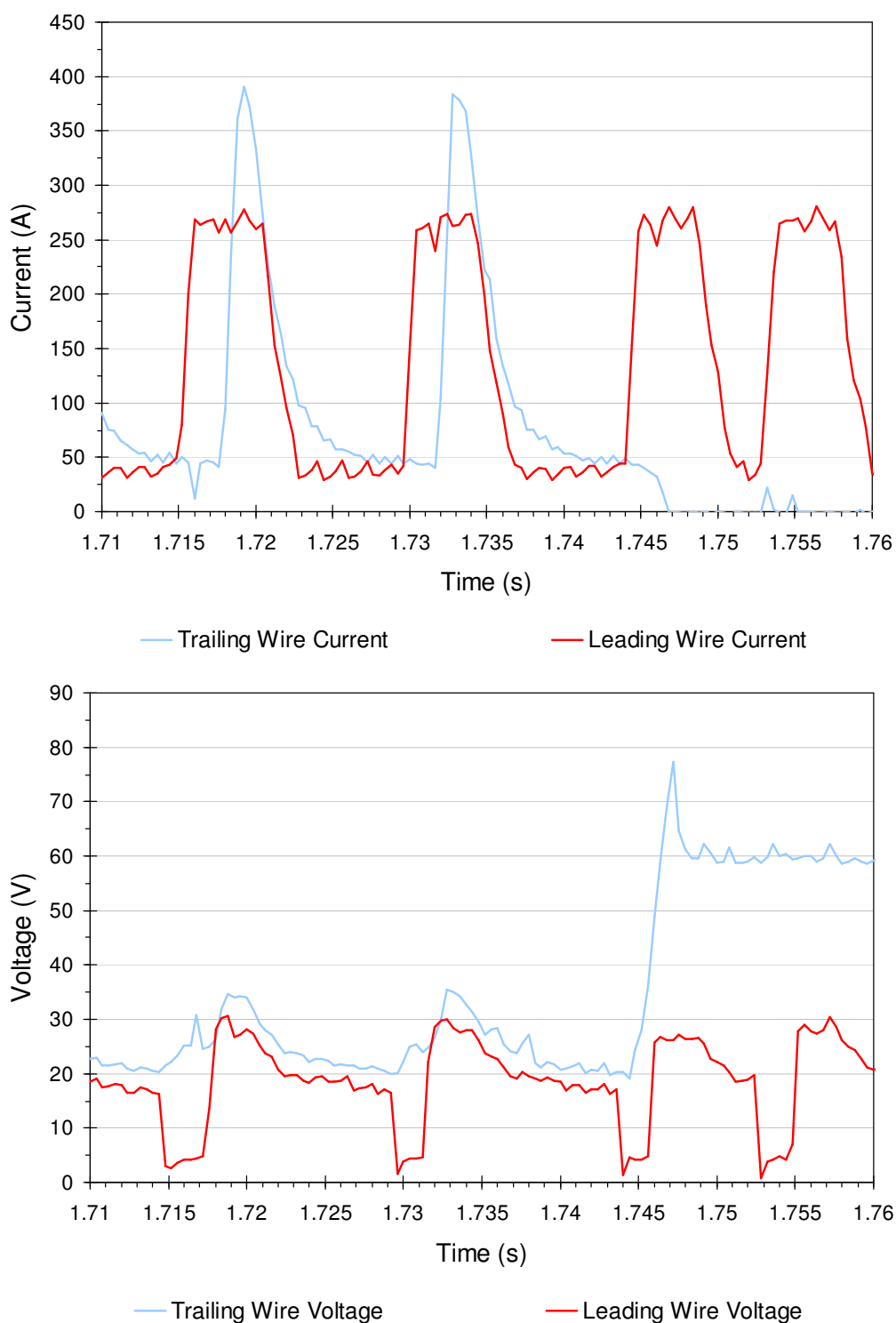


Figure 4.90: Pulse of current in the trailing wire applied too late to avoid interruption

Taking the result of the first modification implemented to synchronise the waveforms into consideration, a second modification was made in the control program to synchronise the pulse of current in the trailing wire (pulsed mode) to a moment after the beginning of state 3 (when the current is raised at the early moments of the short-circuiting period) in the

controlled short-circuit process (a delay could be selected in the interface to change the instant of the pulse in the trailing wire). The current waveform in the trailing wire was defined as described before with the time in the base current ended by the frequency of short circuiting in the leading wire. Figure 4.91 illustrates the consequential synchronisation.

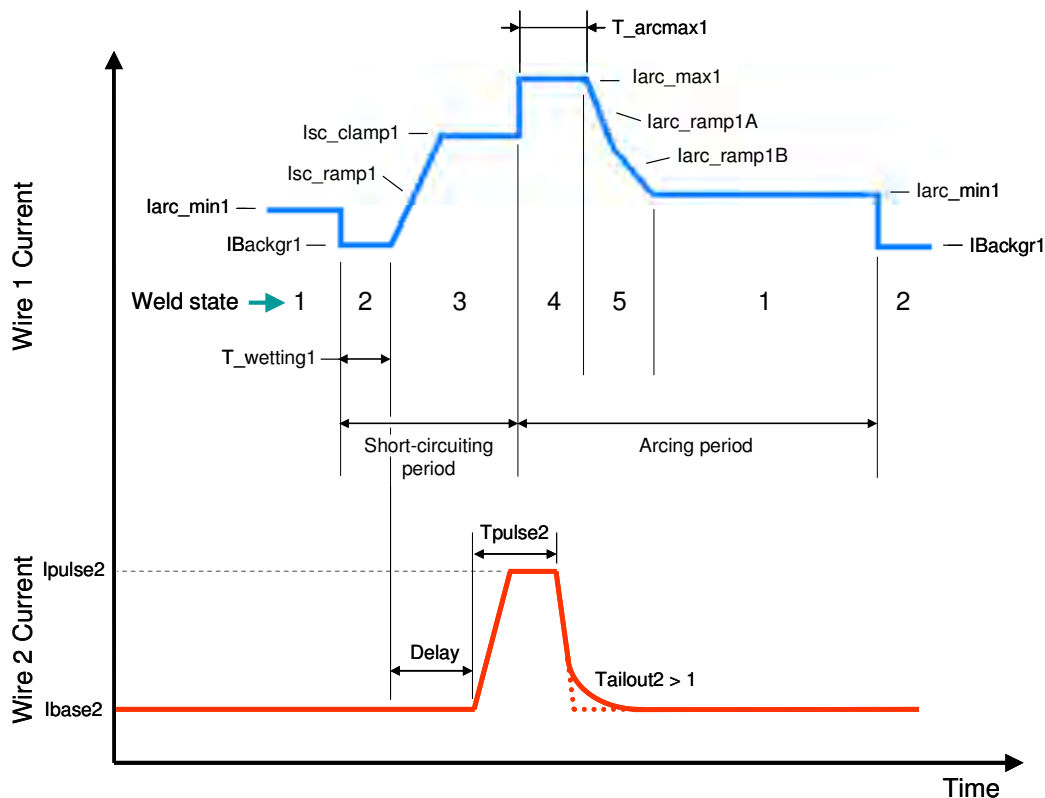


Figure 4.91: Pulse of current applied in the trailing wire a moment after the beginning of state 3 in the controlled short-circuit process

Despite the fact of still having a frequency of short circuiting with a mean period of about 16 ms (close to a period of 18 ms used with success for pulsed welding), this modification was also unable to avoid the arc interruptions. The interruptions may be still taking place due to the fact that when the current is going down to the base level after the pulse of current in the trailing wire, the level of current in the leading wire is still high (pulse of current after the end of the short circuiting). In other words, the pulse of current in the trailing wire may be not being long enough (Figure 4.92), which leads to the scenario favourable to interruptions.

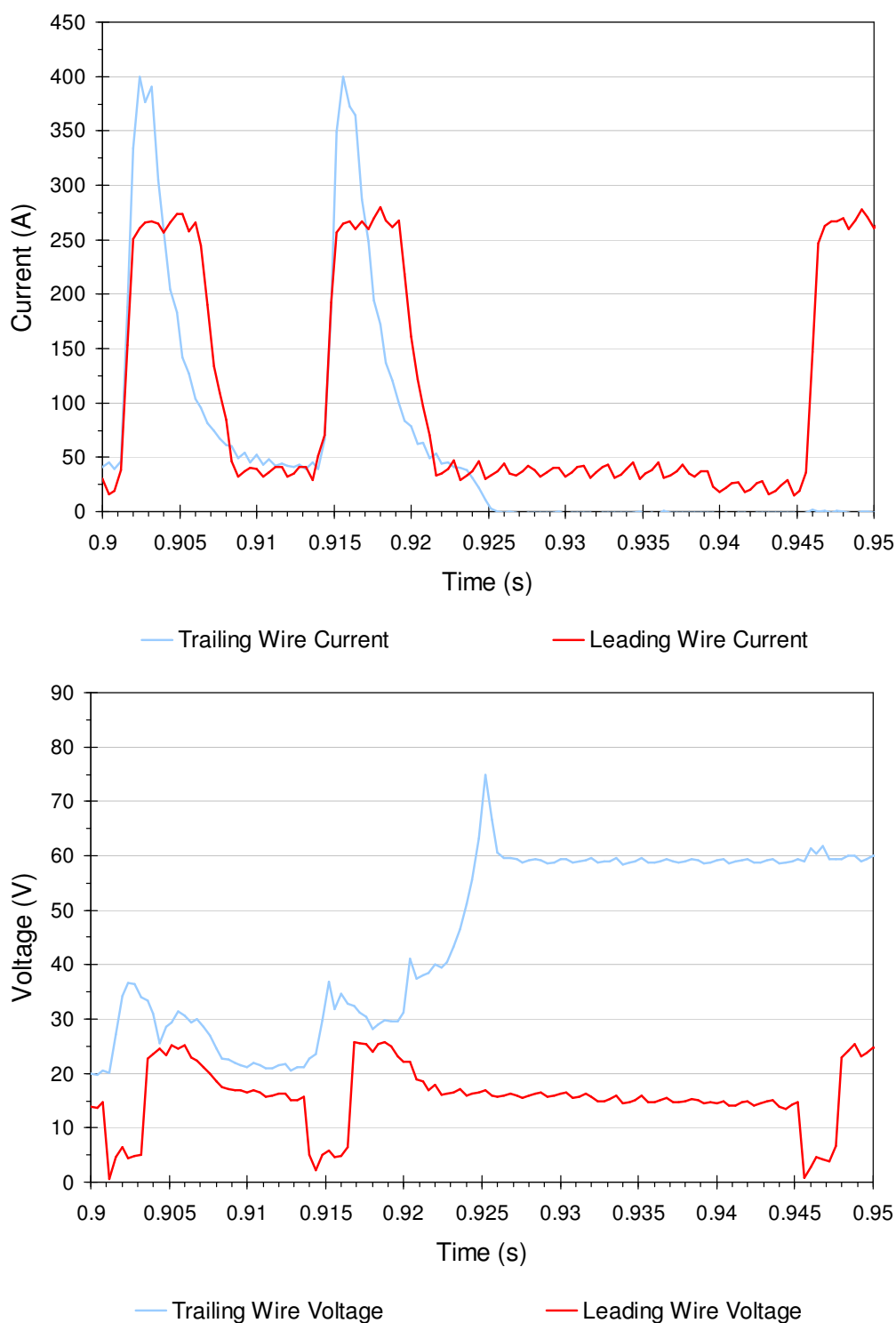


Figure 4.92: Pulse of current in the trailing wire not long enough to avoid interruption

Before trying to use a long pulse of current in the trailing arc in order to cover the time that the current in the leading wire is in a high level, another modification was made in the control software regarding the synchronisation between the wires. This time it is possible to

start the pulse of current in the trailing wire straight after the beginning of state 2 of the controlled short-circuit transfer (leading wire) (a delay can still be selected) (Figure 4.93).

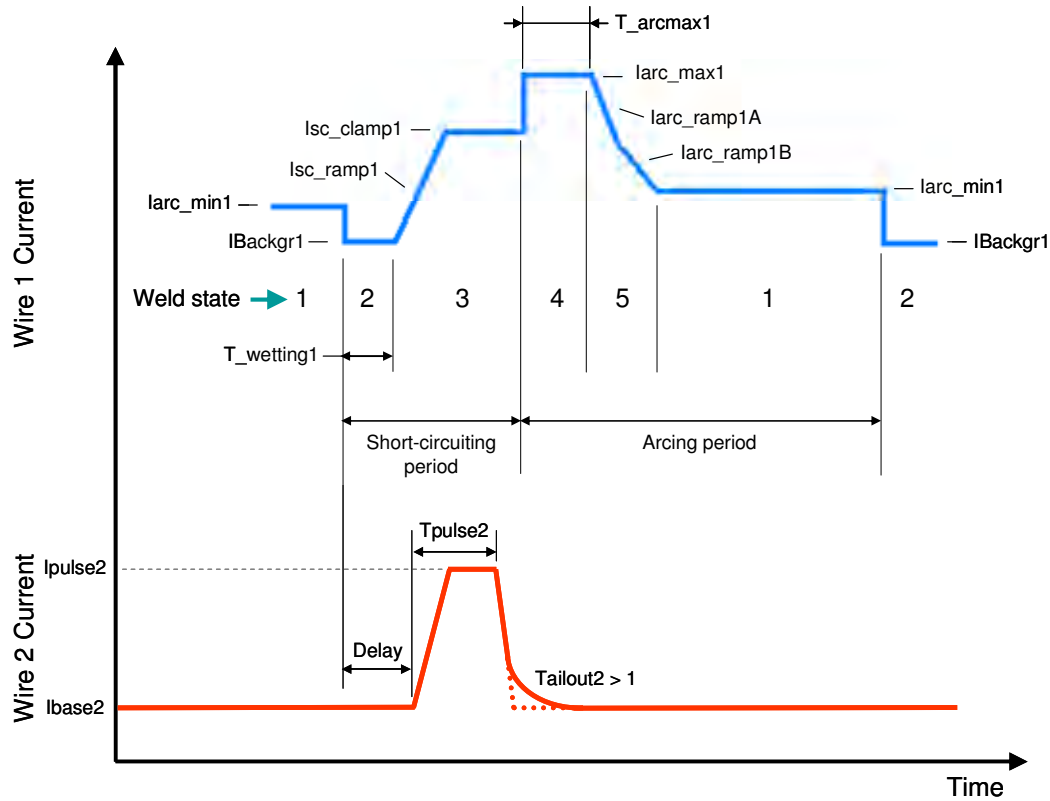


Figure 4.93: Pulse of current applied in the trailing wire a moment after the beginning of state 2 in the controlled short circuit process

In order to increase the duration of the pulse of current in the leading wire yet with conditions likely to promote detachment of one droplet per pulse, the relationship $I_p^n t_p = D$ was used (I_p is the pulse current amplitude, n is a process dependent factor and D is the detachment constant). Taking into consideration the welding conditions used, a value of 2.3 was utilized for the n value (Palani; Murugan, 2006). Considering this n value, a value for D was found based on previous conditions used for pulsed mode known to provide one droplet per pulse of current applied ($I_p = 350$ A and $t_p = 2$ ms). Since the time that the leading wire stayed in high level of current for short-circuit transfer mode for the conditions being used was verified to be roughly around 5 ms, a 5 ms current pulse should be applied to the trailing wire in the pulsed mode. According to the relationship I_p versus t_p above, a pulse lasting for 5 ms should have a level of around 235 A. So the new pulse in the current waveform in the trailing wire was defined by a current of 235 A and a duration of 5 ms. As shown by Figures 4.94 and 4.95 this low and long pulse of current in the trailing wire improved the process regarding the occurrence of interruptions, with long times of data acquisitions being verified

without interruptions in the trailing arc. However, the process (control program) still does not have features to deal with unexpected events, such as a long short circuiting taking place in the leading wire, which may make the duration selected for the pulse of current in the trailing wire (fixed) not enough to avoid the interruptions (Figure 4.96).

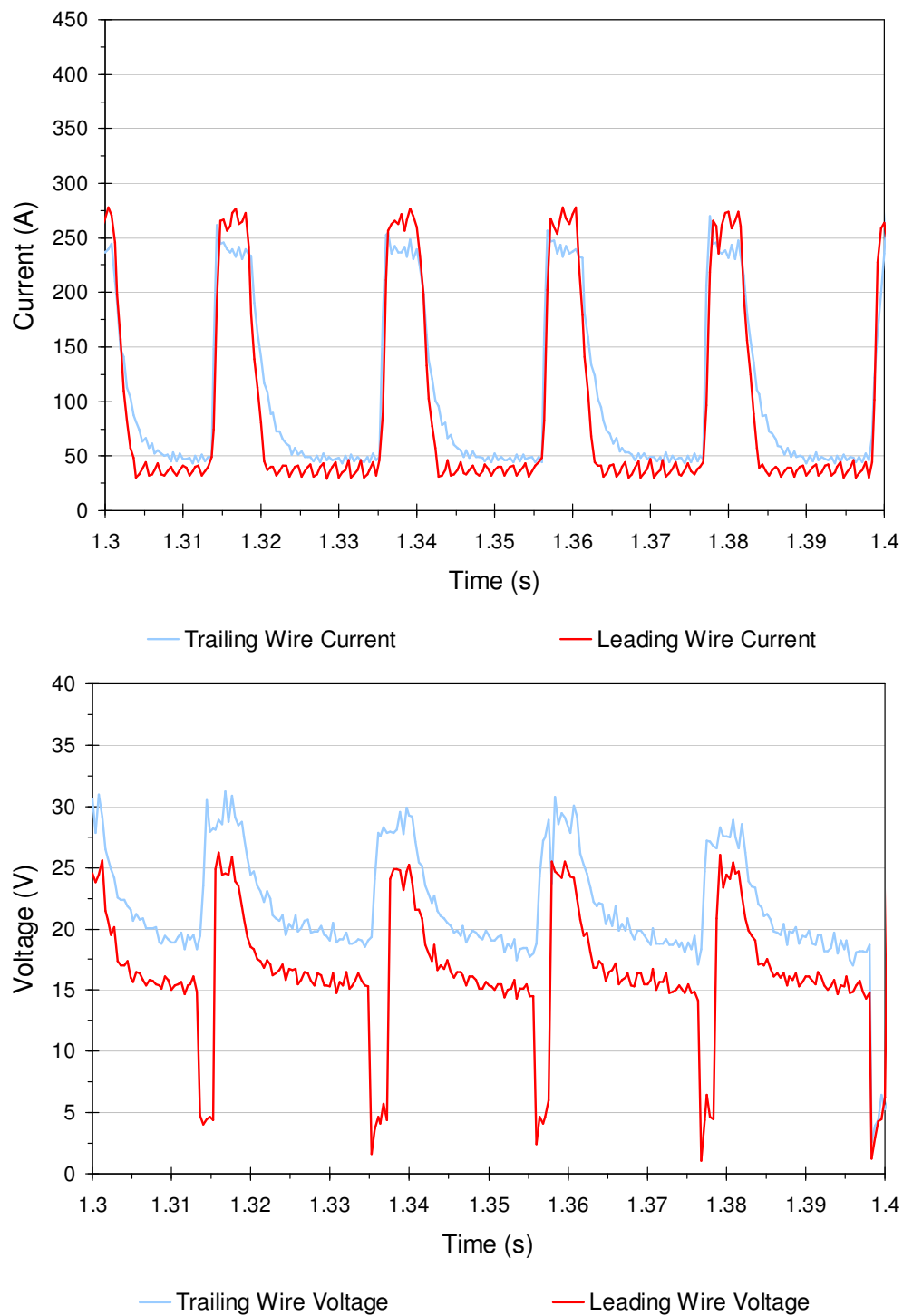


Figure 4.94: Long pulse of current in the trailing wire to cover the pulse in the leading wire (help in avoiding interruptions)



Figure 4.95: Weld bead aspect produced by TandemOptPulse program (synchronisation after state 2 of controlled short-circuit mode and long/low current pulses)

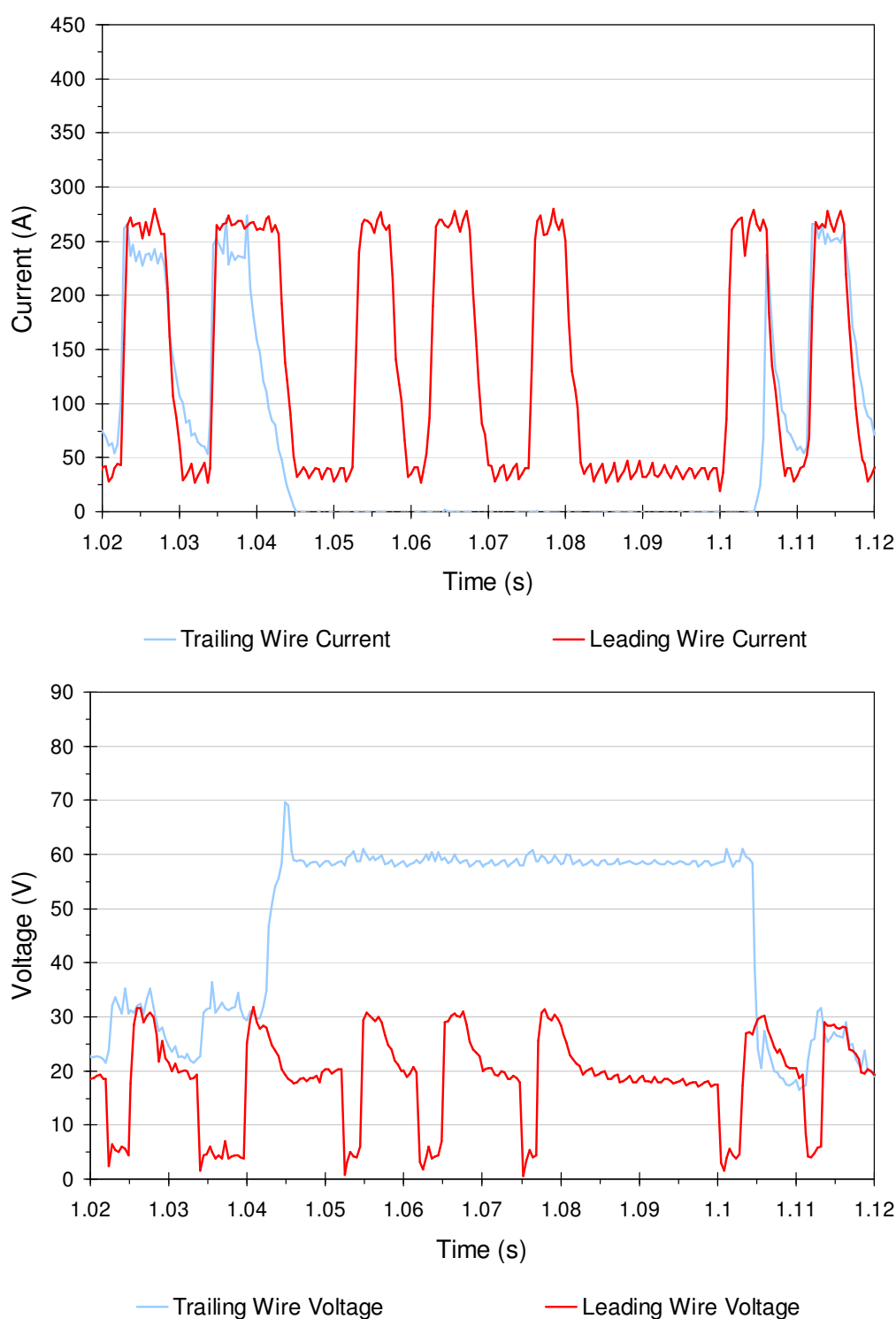


Figure 4.96: Long pulse of current in the trailing wire to cover the pulse of current in the leading wire (interruption when short-circuiting time in the leading wire is too long and pulse in the trailing wire is not long enough to cover the “pulse” in the leading wire)

The concept developed to avoid arc interruptions in the trailing wire seems to cover only very stable conditions for the leading wire (high stability index with regular short-

circuiting time), reason why the control must be improved to deal with unexpected events, such as long short-circuiting periods in the leading wire, etc. In order to improve the control, the current waveform in the trailing wire was modified in the control software within a defined range to have a current level just high enough at the first stages of the pulse to avoid interruptions (intermediate level) and with a higher level in the end to promote the detachment of the droplet. In this case the pulse configuration is something similar to a two-steps pulse of current (Figure 4.97). Despite the modification being able to run the process for long times without interruptions (Figure 4.98) and with reasonable weld beads (Figure 4.99), the process still shows intervals of great instability and does not have repeatability.

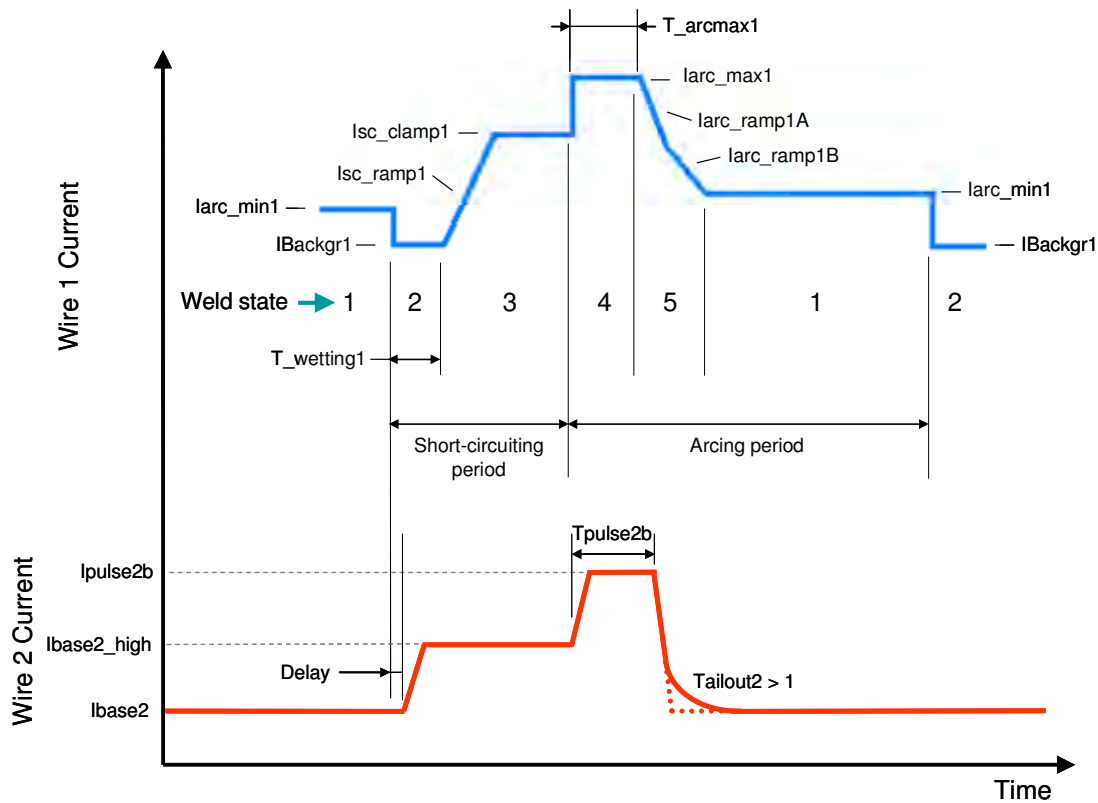


Figure 4.97: Pulse of current in two steps applied in the trailing wire a moment after the beginning of state 2 in the controlled short-circuit process

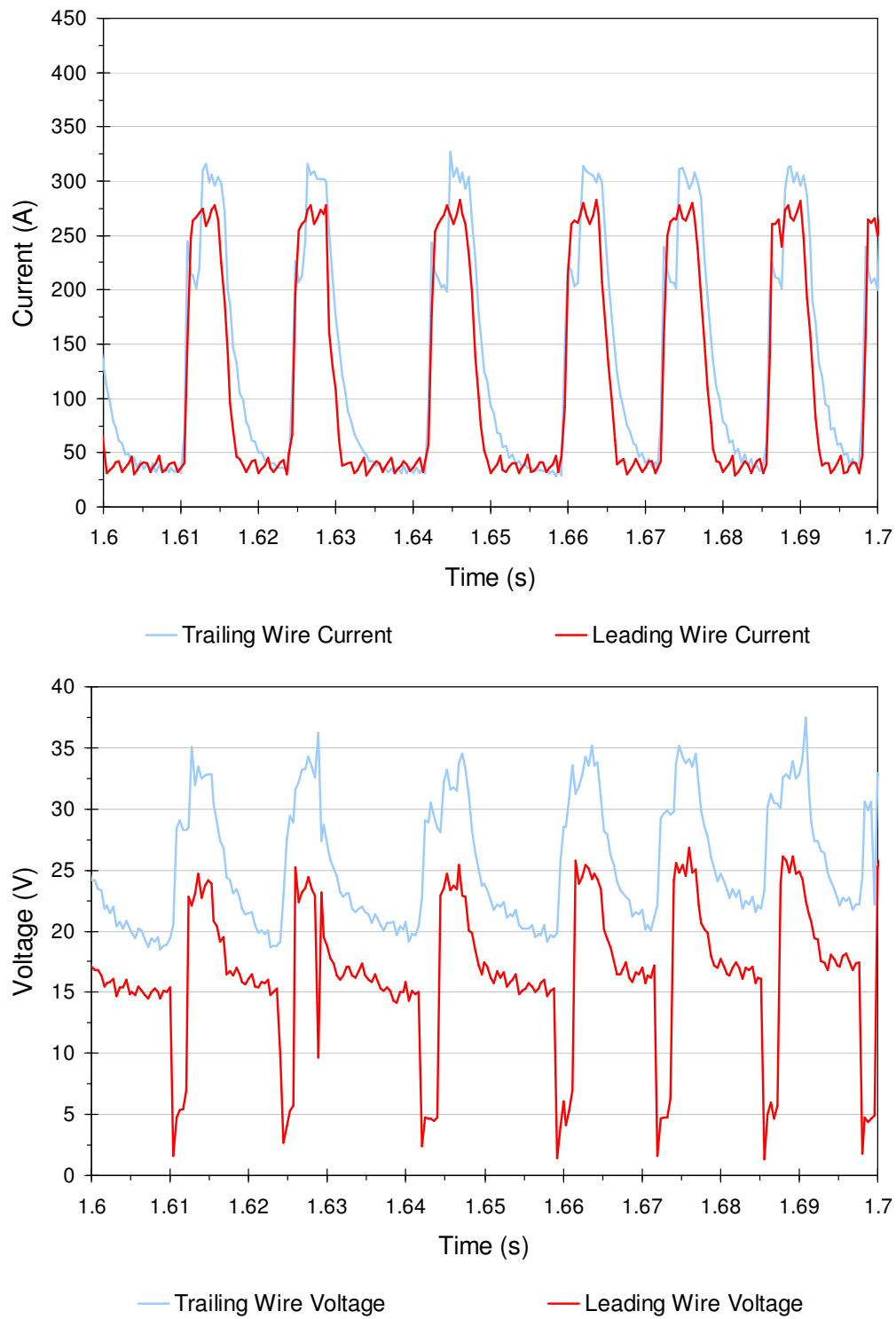


Figure 4.98: Pulse of current in two steps applied in the trailing wire to cover the pulse in the leading wire (help in avoiding interruptions)



Figure 4.99: Weld bead aspect produced by the TandemOptPulse program with two-steps pulse of current (synchronisation after state 2 of controlled short-circuit mode)

Considering the results of the assessment carried out for the TandemOptarc program (item 4.4), it is possible that the weld pool is under great influence of the pulses from both wires and its oscillation influences the short-circuiting cycle in the leading wire. The range of variation allowed to the two-steps pulse of current applied in the trailing wire seems to be not enough to deal with the degree of instability generated by this approach for tandem GMAW. The process seems to show a very narrow operational window and also with a high degree of difficulty to find a stable welding condition (large number of variables and interdependence between them), which make the process unfeasible by this time. However, variables like wire diameter, shielding gas, etc., and other combinations of welding parameters must be tried in conjunction with high-speed filming to determine whether the process can be feasible or not.

4.5.4 General comments

The first version of the TandemOptPulse program was designed to use controlled short-circuit GMAW in wire 1 (leading) and pulsed GMAW in wire 2 (trailing) and presents an amicable user interface and high flexibility for parameters setting. The program was totally able to control the parameters (current waveform) for both wires. By these features this program becomes another important tool in order to investigate options of GMAW used in tandem approaches.

Despite being able to control the processes (controlled short-circuit and pulsed modes) independently, some modifications were made in order to control the trailing wire (pulsed mode) based on what takes place on the leading one, allowing more control over the two process together. Such modifications were made in order to avoid or minimise the occurrence of interruptions in the trailing wire and basically consisted of synchronising the pulse of current in the trailing wire to the moment the leading wire is at the beginning of the short-circuiting period and extending the duration of the pulse of current to cover the time the leading wire is in a high level of current. These modifications showed to improve the process

but there was not repeatability. The process seems to have a very narrow operational window, which makes any application prospect unlikely at this stage of development.

Further investigations with different parameters and welding conditions should be tried before continuing with the modifications in the control program. Thinner wires should be tried, for instance, since Dean (2003) found high stability indexes using the controlled short-circuit method used in this work for single GMAW in such a case.

CHAPTER V

STUDY ON LASER BEAM APPLICATION

5.1 Introduction

A large number of research and development has been conducted recently on the use of Laser in welding operations, turning this process into an important tool for a variety of applications. Although it is possible to use the Laser beam as a unique source of heat to promote union of materials, the combination of the beam provided by a Laser system with a 'conventional' welding process has become largely studied and applied in the so called hybrid welding. Regardless of the process chosen to be combined with the Laser, the general and eventual result is the increase in the effectiveness of the welding. The combination of LBW (Laser beam welding) and arc welding tends to enhance the advantages and compensate the limitations found in each process. Generally the final result is an increase in the weld penetration depth, width and welding travel speed.

Despite all these facts, there are many issues still requiring further research and development on the use of hybrid welding with Laser and arc processes, including more comprehensive understanding on the various welding phenomena involved and the exploration of new combinations. This chapter describes a new approach for hybrid welding combining LBW with tandem GMAW. The first view at such hybrid process is described and some basic aspects regarding its performance are discussed.

5.2 Equipment Setup

As a means of allowing a new approach for hybrid welding using LBW and GMAW a new rig was designed to provide support for the components of the tandem GMAW torch whilst providing accommodation for a Diode Laser head. As the Laser head is placed between the wires its beam can be used perpendicular to the workpiece, meaning that the

Laser beam can deliver its energy with maximum efficiency. As shown by Figure 5.1, a mounting piece for the Laser head was put between the wires with adjustment for the Laser beam focus and the capability to vary the inter-wire distance for the tandem GMAW process was kept. Figure 5.2 shows the final rig with the Laser head already installed. Figure 5.3 shows the test facility diagram for Laser - tandem GMAW. Figure 5.4 shows the Laser system and head used. The GMAW power sources used were the same as for the tandem GMAW approaches assessed previously (Figure 3.15). As shown by Figure 5.5, the start-control for the tandem GMAW was modified by adding an ON-OFF switch to enable (ON) or unable (OFF) the Laser to the process. Through the WELD ON / WELD OFF switch both processes (LBW and tandem GMAW) can be started and ended if the LASER ENABLE switch is set ON.

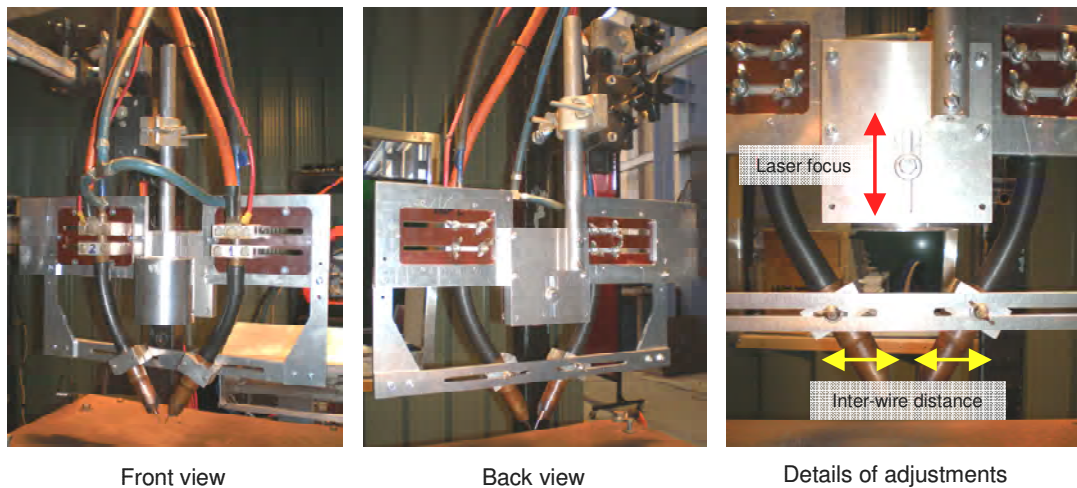


Figure 5.1: Details of the Laser - tandem GMAW rig without Laser head



Figure 5.2: Laser - tandem GMAW rig with Laser head assembled

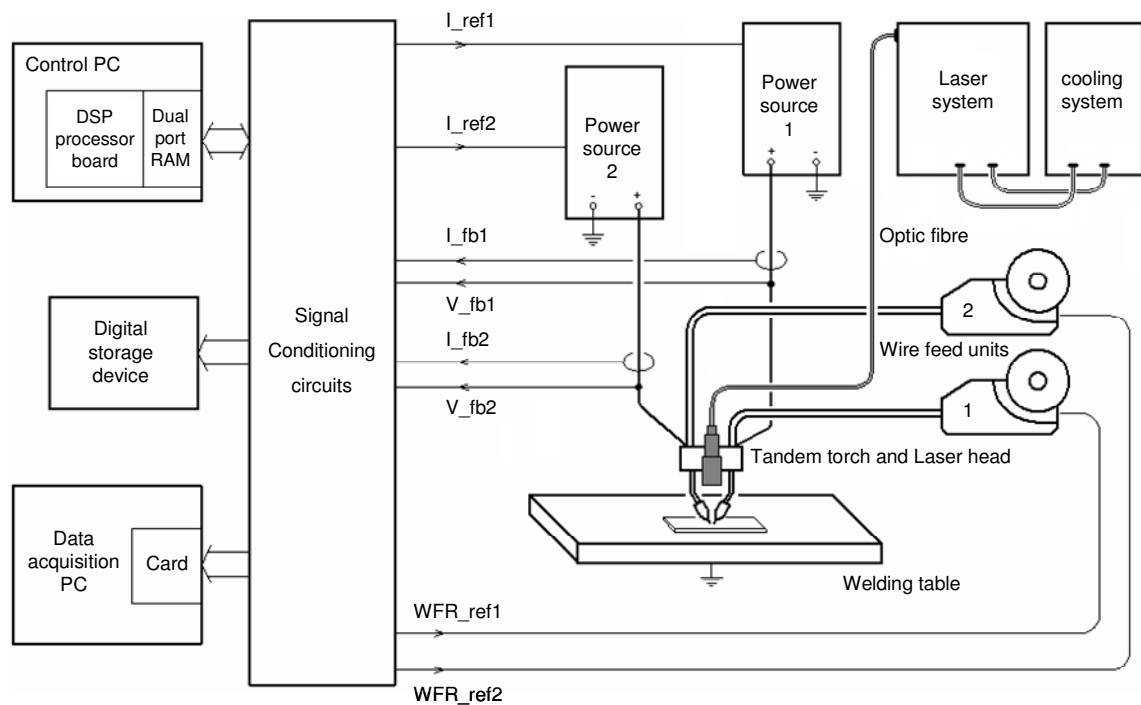


Figure 5.3: Test facility diagram for Laser - tandem GMAW



Figure 5.4: Laser system (left hand side) and Laser head (right hand side)

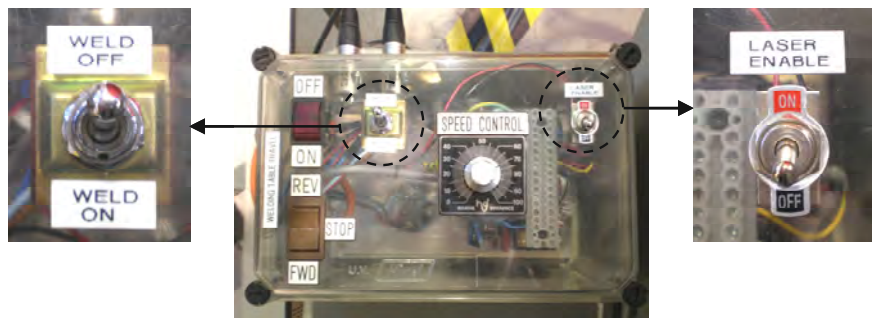


Figure 5.5: Laser enable control (detail on right hand side) added to the tandem GMAW start-control

In order to use the Laser beam with maximum efficiency, a simple experiment was carried out to have a reference line to the Laser beam focus point. This experiment was based on the fact that, given a constant time of application on a base material, after stabilisation the Laser beam will produce the smallest mark (hole diameter) when its focus point is on the plate surface (maximum energy concentration). A piece of polymer was used as the base material and the Laser equipment was programmed to produce a constant 100 W beam for 5 seconds. The range of distances to be verified was chosen considering the fact that the focus point of the Laser beam is located 200 mm from the last internal lens of the head. A number of holes were produced in the polymer plate within the distance range and the diameter of these holes checked using a digital vernier. Figure 5.6 illustrates the process followed to determine the Laser beam focus point. Table 5.1 presents the distances verified with the respective diameters whilst Figure 5.7 shows the results of this verification

graphically. According to the results, the Laser beam focus point is situated between 92 and 97 mm from the reference adopted. In order to facilitate its setting, the Laser head was placed 94.5 mm (mean point of the region of focus) distant from the plate and a reference line was marked on the rig 200 mm from the polymer plate (Figure 5.8).

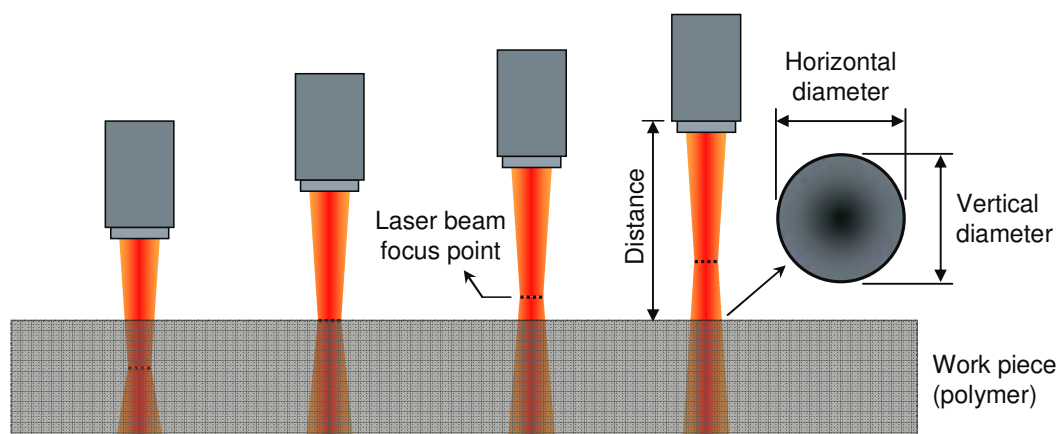


Figure 5.6: Illustration on how the Laser beam focus point was determined

Table 5.1: Results to determine the Laser beam focus point

Distance (mm)	Diameter (mm)		
	Horizontal	Vertical	Mean
117	6.30	6.25	6.27
115	6.21	6.16	6.18
113	6.06	6.08	6.07
111	5.77	5.79	5.78
109	5.71	5.69	5.70
107	5.14	5.10	5.12
105	5.05	5.05	5.05
103	4.72	4.68	4.70
101	4.64	4.61	4.62
99	4.58	4.53	4.55
97	4.29	4.23	4.26
95	4.37	4.27	4.32
92	4.30	4.26	4.28
90	4.39	4.30	4.34
88	4.61	4.57	4.59
86	4.67	4.64	4.65
84	4.74	4.73	4.73
82	4.81	4.86	4.83

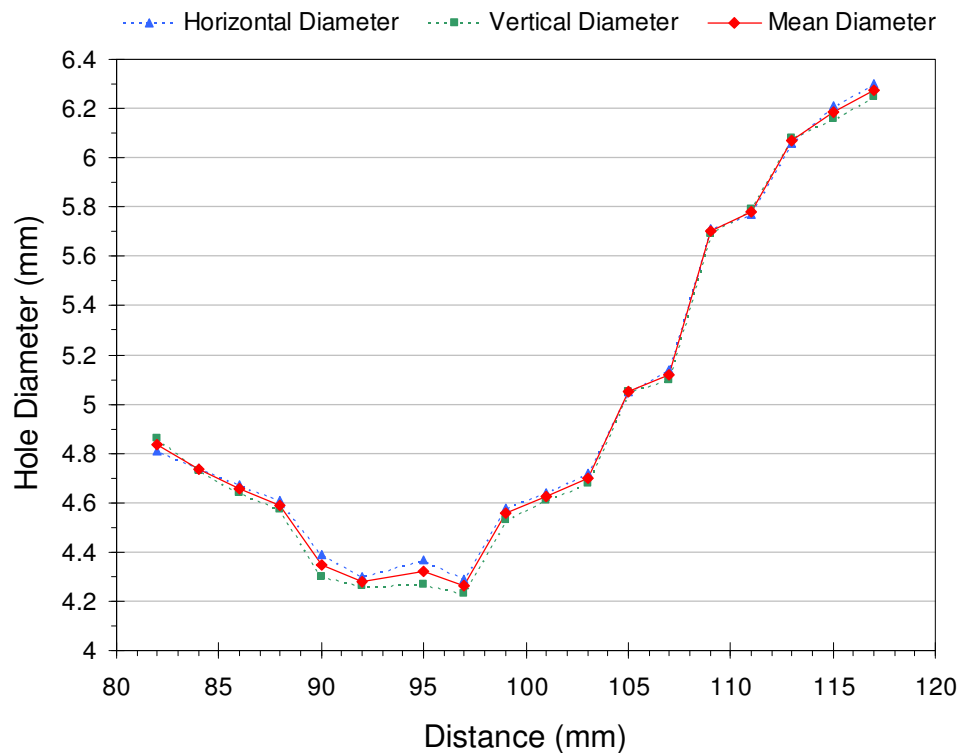


Figure 5.7: Laser beam focus point region (range for minimum hole diameters)

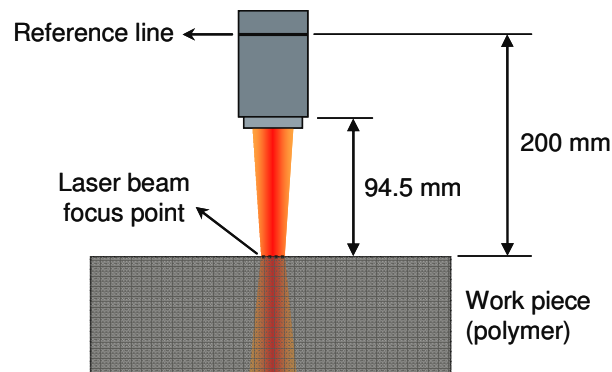


Figure 5.8: Illustration of Laser beam focus reference line

5.3 First Evaluation of Laser - Tandem GMAW Process

As the use of a Laser beam between the wires in a tandem GMAW torch is a new approach for hybrid welding, some basic evaluation of the process is needed. Some of the first points that come to mind are about the position of the Laser beam in relation to the wires, whether the Laser beam allows increased inter-wire distances to be used, and the effect caused by adding the Laser beam between the wires on the weld bead profile. In order to accomplish an evaluation on the first two aspects, some tests were carried out varying the position of the Laser beam between the wires whilst varying the inter-wire distance for two

Laser beam power levels (1 and 2 kW). According to the illustration in Figure 5.9, the Laser beam was tried at the mean distance between the wires (position C), centralised between the mean point of the inter-wire distance and the trailing wire (position T), and centralised between the mean point of the inter-wire distance and the leading wire (position L). An evaluation on the effect of adding the Laser beam to the tandem GMAW process on the weld bead profile is carried out in the end.

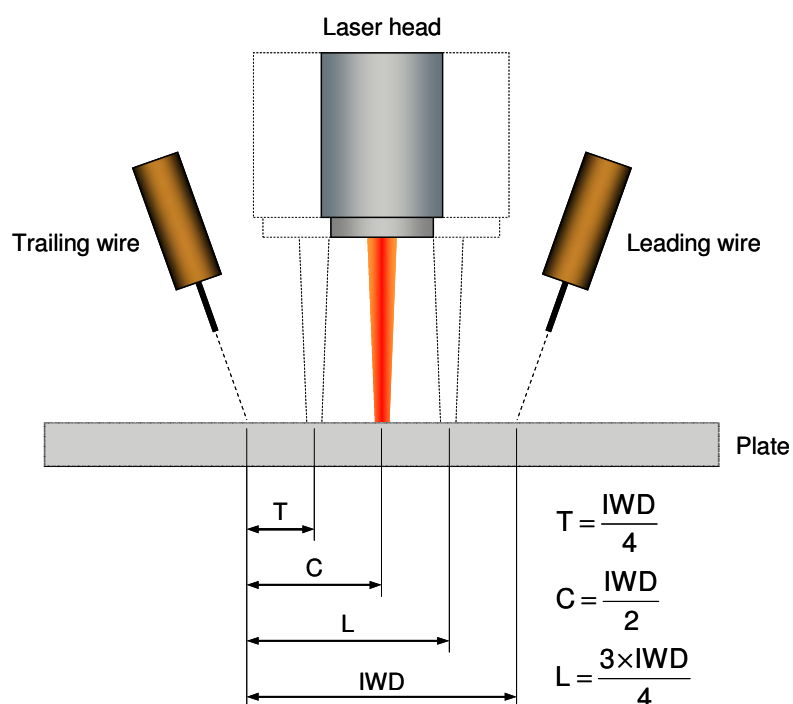


Figure 5.9: Position of Laser beam in relation to the leading and trailing wire
(IWD = inter-wire distance)

The tandem GMAW mode chosen to be tried in this new hybrid welding approach was the pulsed mode. A condition derived from the optimized low mean current condition defined before was tuned ('almost-in-phase' current pulses providing one droplet per pulse and no arc interruptions) considering the small changes in the welding setup (GMAW torch angle, etc.). For each position of the Laser beam in relation to the wires and Laser beam power level, three weld beads were produced; one to provide opportunity to capture images synchronised with transient electrical data and two to provided long electrical transient data acquisition time and assess the repeatability of the process. For the cases in which the Laser beam was centralised between the wires and with high level of power, the conditions were tried also using out-of-phase pulsed welding (10 ms of delay between the current pulses, delivering the pulse of current in the trailing wire when the leading wire was in the middle of its base current time and vice versa). Weld beads were produced also using only the Laser

beam (1 and 2 kW) and only the tandem GMAW process (0.1 ms and 10 ms of delay between the current pulses) as a comparison basis. Table 5.2 shows the welding parameters used in the pulsed control program developed for tandem GMAW (item 4.1) whilst Table 5.3 shows extra welding parameters. Figure 5.10 shows the angles for the wires in the tandem torch (the angle used was bigger than the usual value as a requirement to accommodate the Laser head between the wires).

Table 5.2: Welding parameters selected for tandem GMAW

Welding Parameter	Value
$I_{pulse1} = I_{pulse2}$ (A)	350
$T_{pulse1} = T_{pulse2}$ (ms)	2
$I_{base1} = I_{base2}$ (A)	50
$T_{base1} = T_{base2}$ (ms)	18
Ramp_up1 = Ramp_up2 (A/ms)	2000
Ramp_down1 = Ramp_down2 (A/ms)	2000
Tailout1 = Tailout2 (dimensionless)	45
WFR1 = WFR2 (m/min)	3.8
Delay (ms)	0.1
Arc Voltage Control (wire 1 and 2)	ON

Table 5.3: Additional welding parameters

Welding Parameter	Value
CTWD* (both wires) (mm)	18
Welding Travel Speed (mm/min)	1626
Shielding Gas [98.5% Ar + 1.5% O ₂] (l/min)	35
Wires diameter [AWS ER 70S-6] (mm)	1.2
Inter-wire Angle (°)	68

* The CTWD parameter was considered as the vertical distance measured from the contact tips to the workpiece.

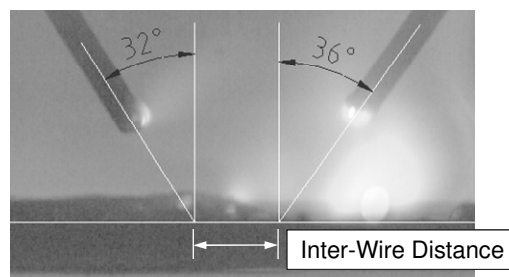


Figure 5.10: Angle measured between the electrodes and inter-wire distance parameter (trailing wire on the left and leading on the right)

The position of the Laser beam between the wires was verified through high-filming. As an example, Figure 5.11 shows the Laser beam being applied centralised (position C) between the wires using 1 and 2 kW of power. It is worth noting the change in size of the Laser plume (ionization of metal vapour and shielding gas) as the Laser beam power is increased. Figure 5.12 shows the aspect of the weld beads produced using the LBW in the two power levels.

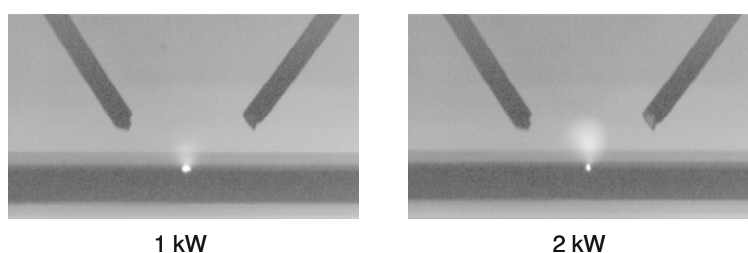


Figure 5.11: Laser beam with different power levels centralised between the wires

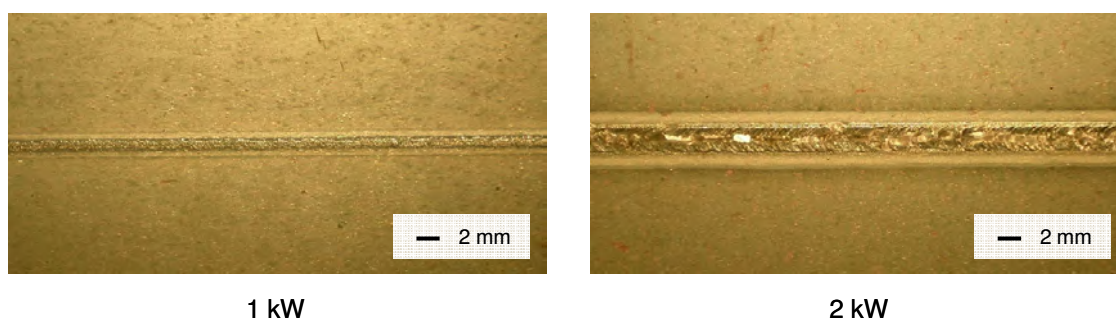


Figure 5.12: Aspect of weld beads produced using the LBW with different power levels (welding travel speed at 175 mm/min)

5.3.1 Visual analysis of the process

Inter-wire distance of 5 mm

The first Laser - tandem GMAW conditions were tried using an inter-wire distance of only 5 mm. Figure 5.13 shows a sequence of images synchronised with electrical transient data for the case of using a 2 kW Laser beam and 'almost-in-phase' current pulses. Figure 5.14 also shows a sequence of images synchronised with the electrical transient data for the case of using a 2 kW Laser beam, but this time with out-of-phase current pulses. As all conditions tried using the Laser beam with an inter-wire distance of 5 mm had similar characteristics, a general assessment of the use of the Laser - tandem GMAW process under these conditions can be carried out through these pictures.

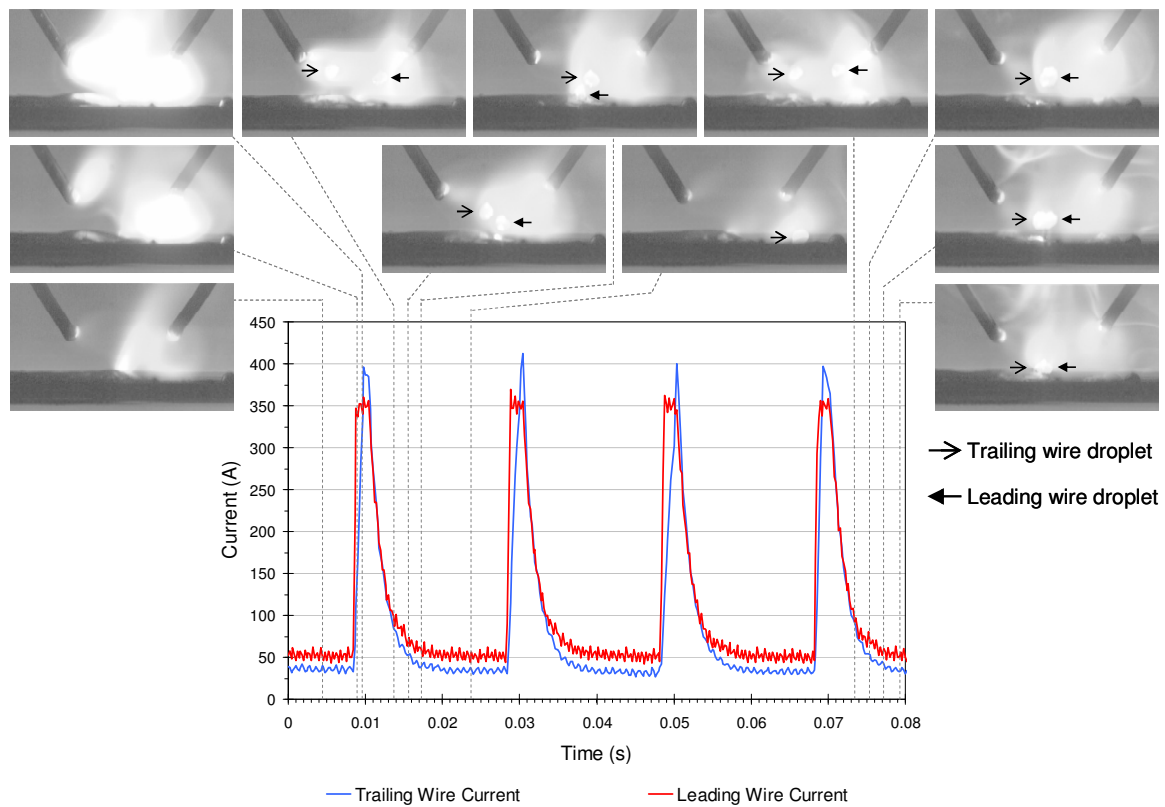


Figure 5.13: Images synchronised with electrical transient data for Laser - tandem GMAW using 'almost-in-phase' current pulses (Laser beam power = 2 kW and inter-wire distance = 5 mm)

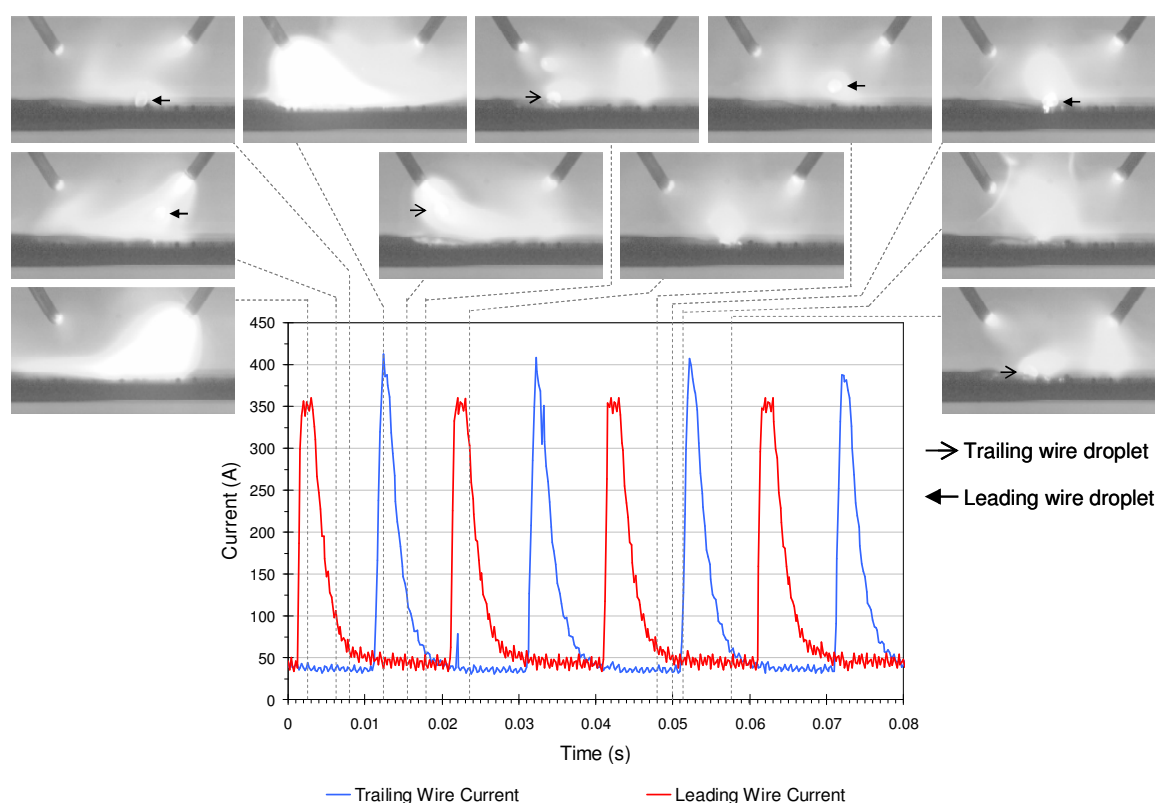


Figure 5.14: Images synchronised with electrical transient data for Laser - tandem GMAW using out-of-phase current pulses (Laser beam power = 2 kW and inter-wire distance = 5 mm)

In the case of 'almost-in-phase' pulses the trailing wire had a tendency of being attracted by the leading arc, but no arc interruptions were observed since the small delay between the current pulses applied to the wires showed to be efficient in avoiding such interruptions even with such a small distance between the wires. A curious phenomenon was detected regarding the metal transfer. The droplets were remarkably deviated and, as a consequence, two situations occurred; the droplets hit the plate out of the weld pool region (especially the droplets from the trailing wire) or they merged close to or right underneath the Laser beam forming a large droplet. In the first case the weld bead aspect is deteriorated since the droplets can hit the plate not necessarily aligned with the weld bead, remaining beside the weld bead and easily identified for their large-spatter shape (Figure 5.15). In the case of merging under the Laser beam, part of the extra energy provided by this process to the hybrid process is lost, since the beam causes partial evaporation of the droplet producing high levels of fume (detail in Figure 5.16). In the case of Figure 5.13, as the trailing arc has been verified as more deviated than the leading one (increasing its actual length and voltage), the AVC lowered the base current in the trailing arc to keep the arc voltage (arc length) as set in the control program. The actuation of the AVC feature is made clear by

observing the average of mean current and voltage (Figure 5.17) of all tests carried out using an inter-wire distance of 5 mm and Laser beam power of 2 kW (as in the case of 'almost-in-phase' current pulses the current and voltage values were calculated considering the Laser beam applied in three positions, error bars (minus and plus standard deviation) are showed). In the case of 'almost-in-phase' pulses, the mean voltage in the trailing arc was kept at the same level as in the leading arc by lowering the respective base current.

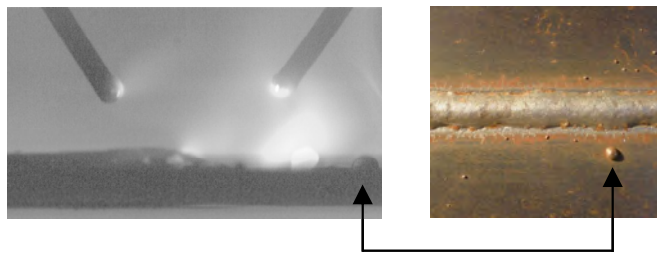


Figure 5.15: Detail of droplet missing the weld bead

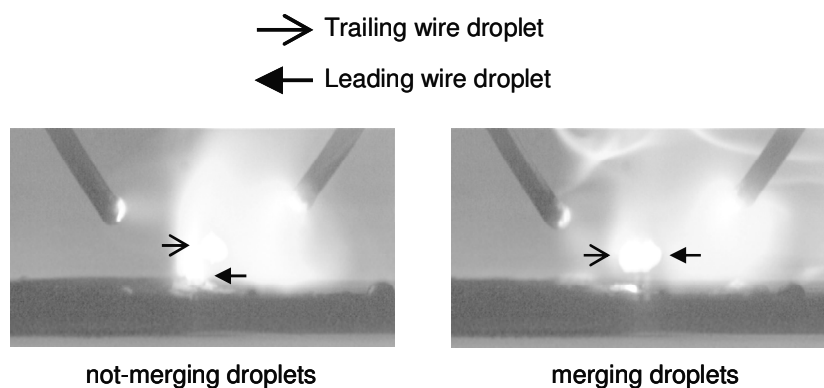


Figure 5.16: Increase in fume generation when merging droplets are partially evaporated by the Laser beam

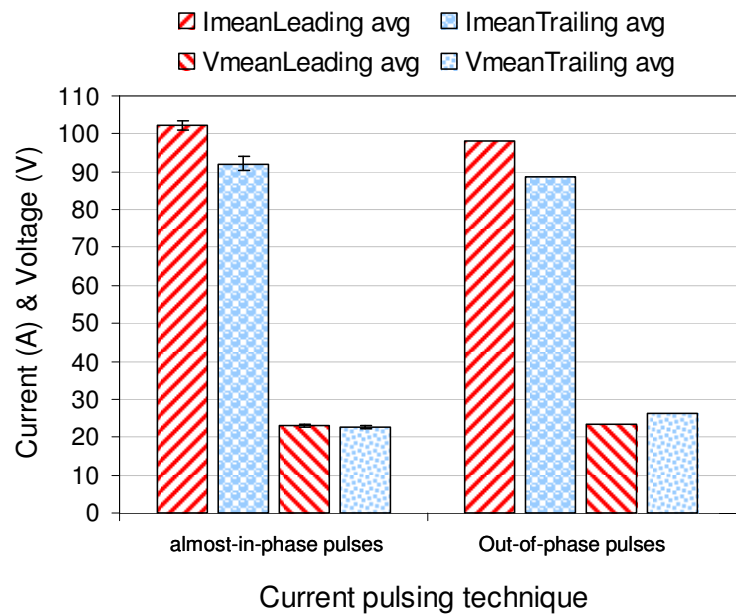


Figure 5.17: Average of mean current and mean voltage values for weld beads produced using an inter-wire distance of 5 mm (Laser beam power = 2 kW)

In the case of out-of-phase pulses, arc interruptions were verified in the trailing wire for all the conditions regardless of adding the Laser beam to the tandem GMAW process or not. Despite these undesirable occurrences, some observations can be made. The droplets were not deviated as much as in the ‘almost-in-phase’ case and they always hit the weld pool without merging, since they were detached from the respective wire at different times, therefore getting to the region underneath the Laser beam at different times. However, the droplets still reached the plate close or under the Laser beam, case in which they were partially evaporated generating more fumes and probably reducing the process efficiency. The mean current and voltage for the out-of-phase pulsing case is shown by Figure 5.17. In the case of out-of-phase pulses, the mean voltage in the trailing arc was higher because of the arc interruptions (the voltage value rises to open circuit voltage value during the interruptions). As a means of comparison, Figure 5.18 presents the mean current and voltage values for the weld beads produced using an inter-wire distance of 5 mm without using the Laser beam.

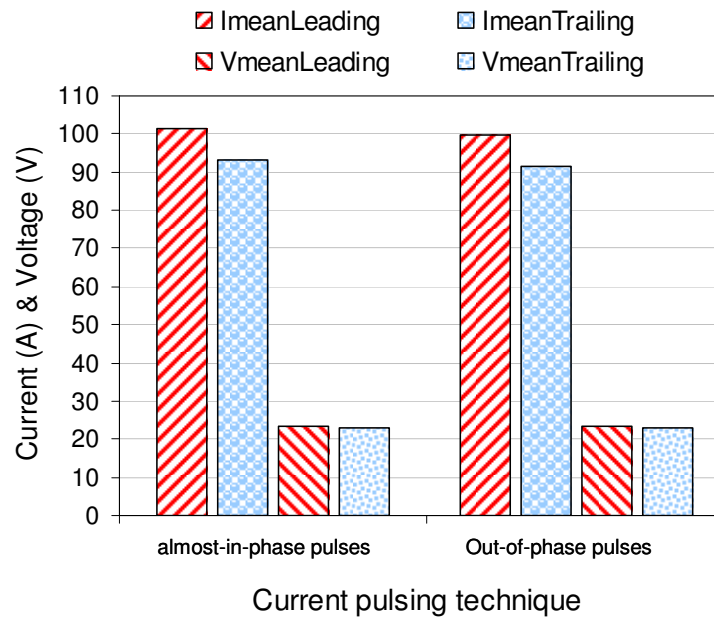


Figure 5.18: Mean current and mean voltage values for weld beads produced using an inter-wire distance of 5 mm without Laser beam

In the case of an inter-wire distance of only 5 mm, the effect of the position of the Laser beam between the wires was not very clear. However, some indications on how the Laser process affects the performance of the GMAW process can be highlighted. Regardless of welding with 'almost-in-phase' or out-of-phase pulses of current for the GMAW process, the Laser beam seemed to have a positive effect on the aspect of the weld beads produced. While the travel speed used was too high for the case of welding without the Laser beam, as the Laser power was increased, the bead aspect was improved (Figure 5.19). As discussed before, the use of 'almost-in-phase' current pulses for such a small inter-wire distance caused the presence of 'large spatters' next to the weld bead. Despite the presence of arc interruptions in the trailing arc in the case of out-of-phase current pulses, the bead aspect did not differentiate significantly because the interruptions were not so long. The out-of-phase pulses even had a positive effect on the weld bead; absence of 'large spatters'.

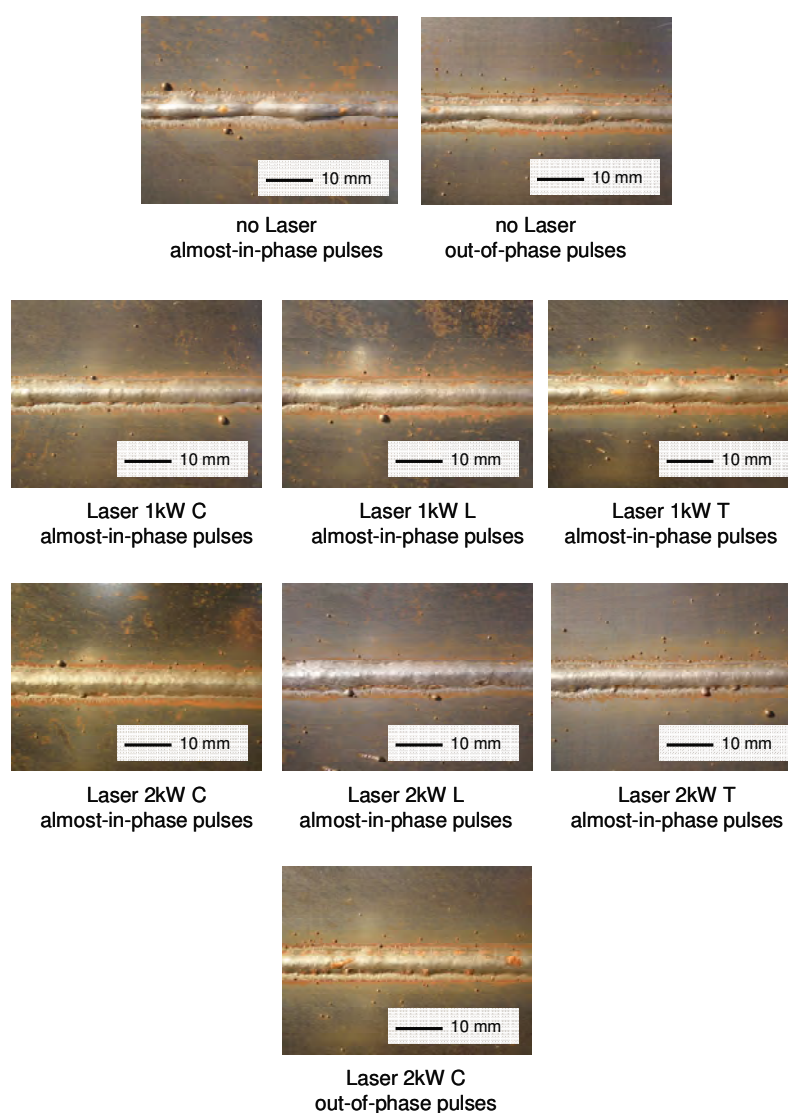


Figure 5.19: General aspect of weld beads produced with Laser - tandem pulsed GMAW using an inter-wire distance of 5 mm (for codes C, L and T see Figure 5.9)

As it was briefly discussed before, a kind of 'cross transfer' occurred when using 'almost-in-phase' current pulses and an inter-wire distance of only 5 mm. This adverse effect had negative consequences in the weld bead aspect, fume generation and probably in the process efficiency. Despite of avoiding arc interruptions, it seems that the fact of having high current levels in both arcs when the droplets are detached left these droplets under more attraction by the opposite arc than when using out-of-phase condition. By observing the videos and transient electrical data when using the tandem GMAW process with out-of-phase current pulses was possible to detect that, even though this condition showed interruptions in the trailing arc, the droplets tended to follow regularly the projection of the respective wire towards the weld pool. In order to give an idea of the magnitude of these deviations, some measurements were carried out. Three aleatory not-merging droplets were

considered for each wire for each pulsing technique. Figures 5.20 and 5.21 illustrate how the droplet deviation was measured for the leading and trailing wire respectively for ‘almost-in-phase’ and out-of-phase pulse conditions. The deviation was considered as the distance between the centre of the ideal droplet and the centre of the actual droplet at the work piece or weld pool level. All measurements were carried out using AutoCAD® and based (calculated) on the leading wire mean actual diameter (1.19 mm). Figure 5.22 congregates the results of droplet deviation measurement for an inter-wire distance of 5 mm. The deviation of the droplets coming from the trailing wire tended to be longer, which is likely to be due to the fact that the trailing arc is subjected to more attraction than the leading one. The reason for more deviation on the trailing arc remains obscure.

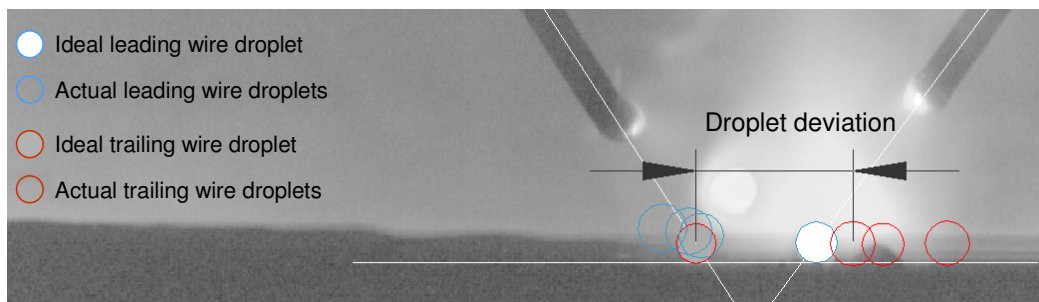


Figure 5.20: Droplet deviation for ‘almost-in-phase’ tandem pulsed GMAW
(inter-wire distance = 5 mm and central Laser beam power = 2 kW)

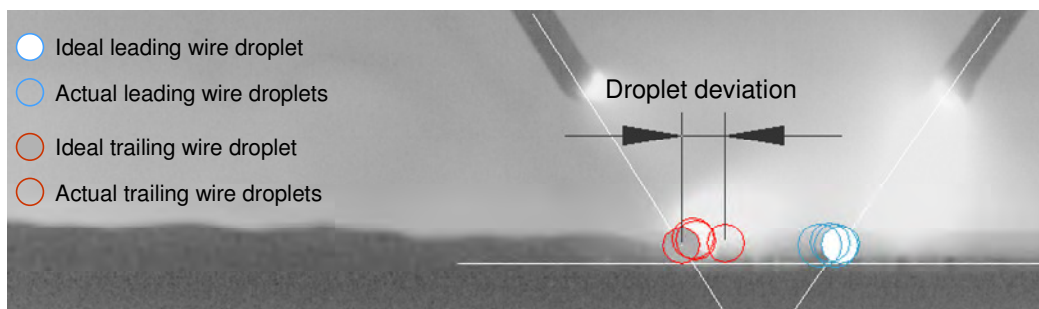


Figure 5.21: Droplet deviation for out-of-phase tandem pulsed GMAW
(inter-wire distance = 5 mm and central Laser beam power = 2 kW)

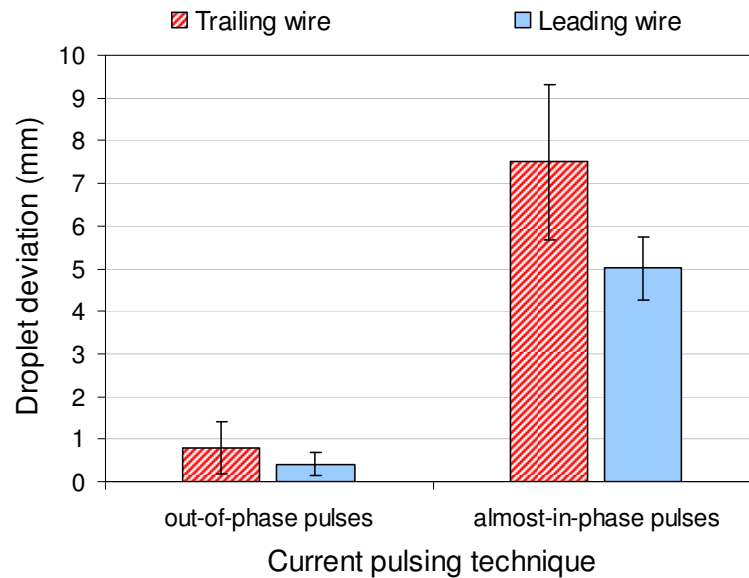


Figure 5.22: Droplet deviation in the leading and trailing arcs for different pulsing techniques (inter-wire distance = 5 mm and central Laser beam power = 2 kW)

As the droplets are under the influence of the same magnetic fields that affect the arcs, it is possible to make an analogy between the droplets deviation and the model of arc displacement proposed by Ueyama et al. (2005) for tandem pulsed GMAW. Despite the use of ‘almost-in-phase’ pulses helps in avoiding the occurrence of arc interruptions by making the trailing arc more “rigid” as the leading arc is at high levels of current, the condition using out-of-phase current pulses decreases the displacement of the arcs (force of attraction) at the moment that the droplets are detached (Figure 5.23). Considering the fact that the plasma jet follows the deviated arc path, the droplets are projected towards the plate following the plasma jet at the moment of detachment and tend to keep their path by inertia. As the force of attraction is reduced, the droplets deviation from the expected path is probably also reduced. According to the model, this decline in the arc deviation (force of attraction) does not take place in ‘almost-in-phase’ (or in-phase) pulses situation (Figure 5.24).

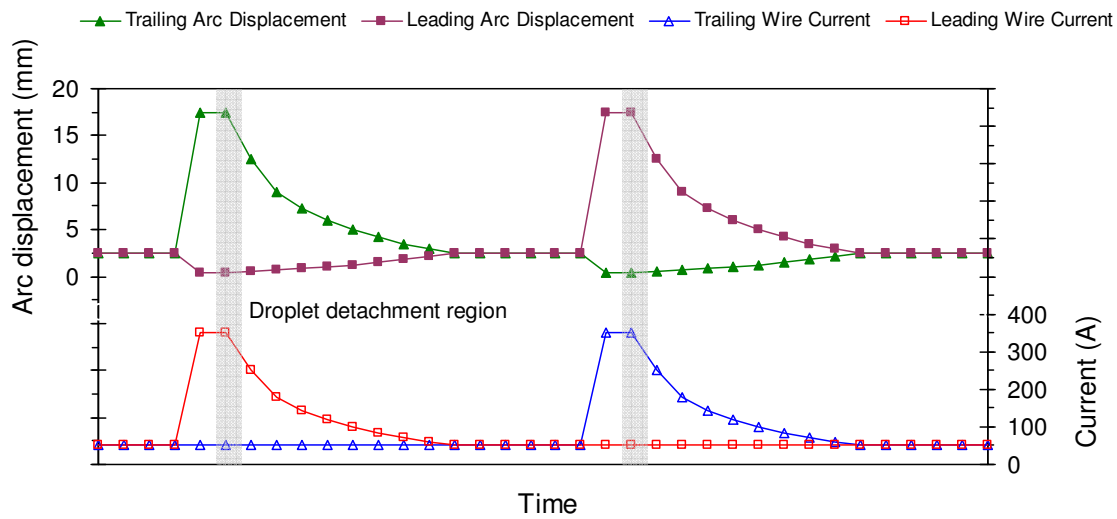


Figure 5.23: Simulation of arc displacement for out-of-phase tandem pulsed GMAW

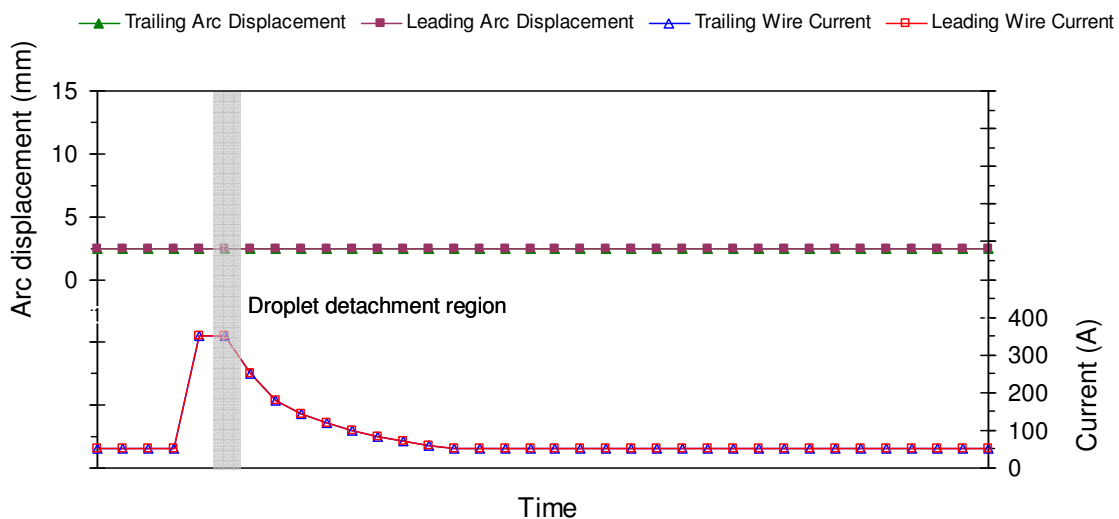


Figure 5.24: Simulation of arc displacement for in-phase tandem pulsed GMAW (coincident arc displacements)

Inter-wire distance of 10 mm

In order to continue the evaluation of the Laser - tandem GMAW process, the inter-wire distance was increased to 10 mm. Figure 5.25 shows a sequence of images synchronised with electrical transient data for the case of using this inter-wire distance with a 2 kW Laser beam and 'almost-in-phase' current pulses. Figure 5.26 also shows a sequence of images synchronised with the electrical transient data for the case of using a 2 kW Laser beam, but this time with out-of-phase current pulses. As all conditions tried using the Laser beam with an inter-wire distance of 10 mm in general presented similar characteristics, a common

assessment of the use of the Laser - tandem GMAW process under these conditions can be carried out through these pictures.

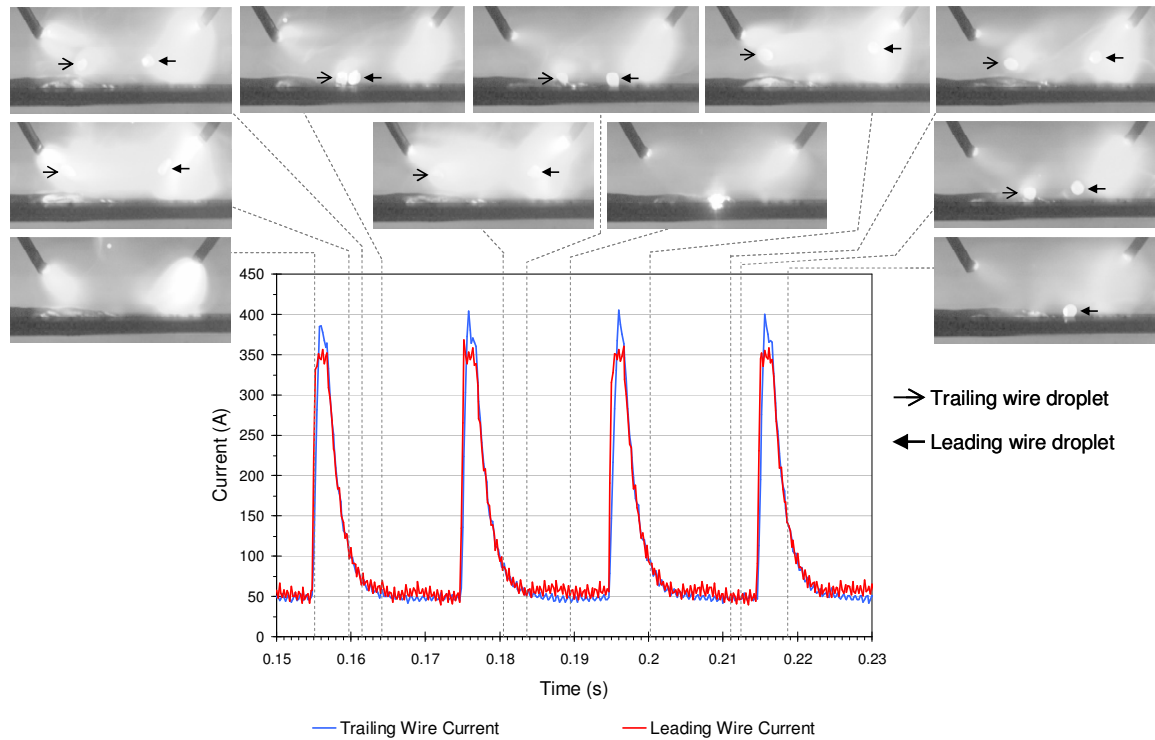


Figure 5.25: Images synchronised with electrical transient data for Laser - tandem GMAW using 'almost-in-phase' current pulses (Laser beam power = 2 kW and inter-wire distance = 10 mm)

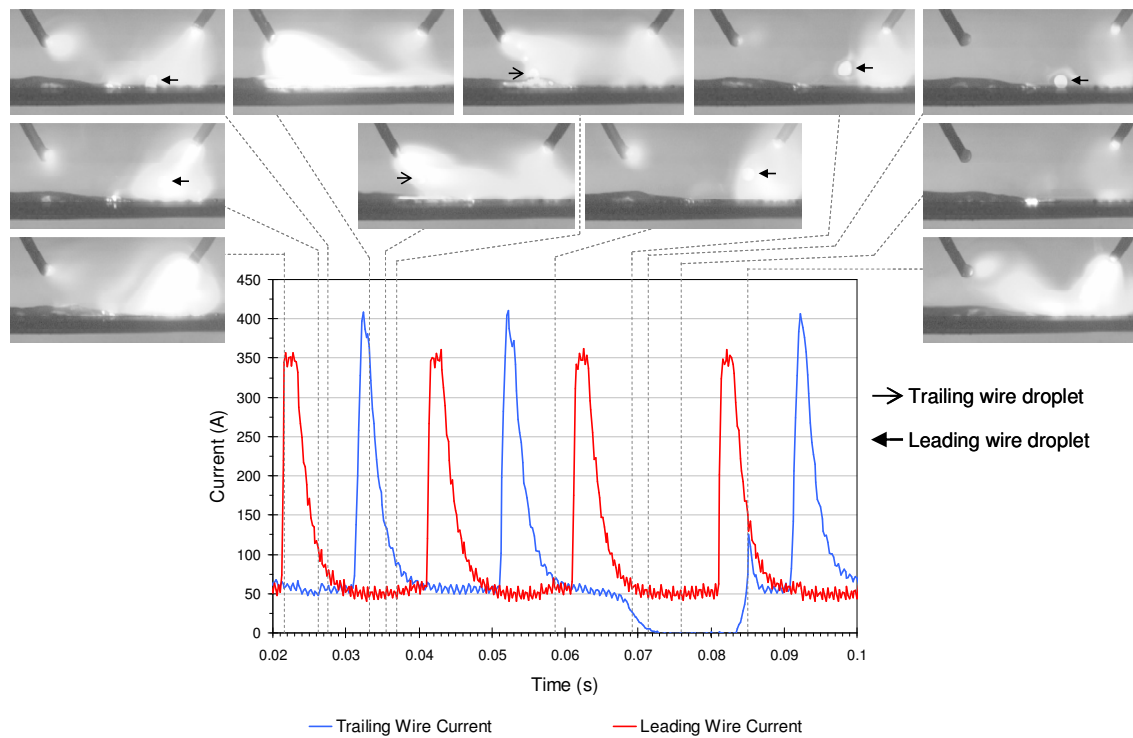


Figure 5.26: Images synchronised with electrical transient data for Laser - tandem GMAW using out-of-phase current pulses (Laser beam power = 2 kW and inter-wire distance = 10 mm)

As it was noticed for the case of an inter-wire distance of 5 mm, the use of ‘almost-in-phase’ pulses caused the trailing wire a small tendency of being attracted by the leading arc, but no interruptions were observed since the small delay between the pulses of current applied to the wires proved to be efficient. As it was expected, the droplets were not deviated as much as when using only 5 mm between the wires. They hit the plate in the weld pool region right next to the Laser beam without crossing their paths or merging (Figure 5.27), which supported the good visual quality of the weld beads produced. The droplets from the leading wire hit the plate close to the leading edge of the weld pool, fact that indicates that the inter-wire distance value may be close to the limit for the welding travel speed used (or the travel speed may be close to the limit for the inter-wire distance used). As the inter-wire distance was increased, the deviation in the trailing arc was reduced (less variation in the voltage value), which minimized the effect on the arc voltage control (the base current values in both wires were very similar). Figure 5.28 shows the average of mean current and voltage values of all tests carried out using an inter-wire distance of 10 mm and Laser beam power of 2 kW. As in the case of ‘almost-in-phase’ current pulses, the current and voltage values were calculated considering the Laser beam applied in three positions. The small difference between the current values in the leading and in the trailing wire is likely to be due to the use

of different power sources for each wire, which respond slightly different to the control program.

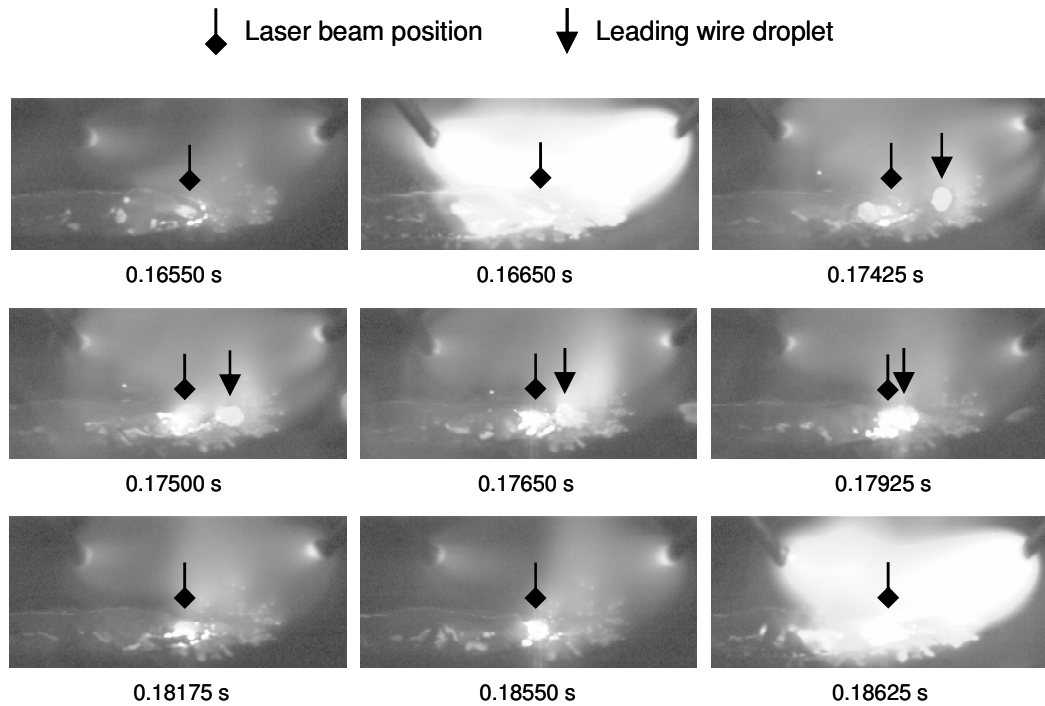


Figure 5.27: Sequence of images showing a droplet originated from the leading wire arriving and being incorporated at the leading edge of the weld pool ('almost-in-phase' pulses, Laser beam power = 2 kW and inter-wire distance = 10 mm)

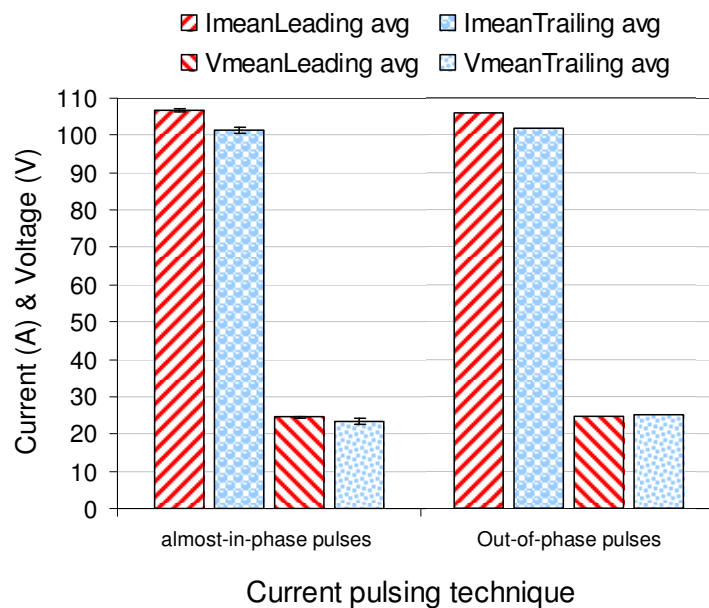


Figure 5.28: Average of mean current and mean voltage values for weld beads produced using an inter-wire distance of 10 mm (Laser beam power = 2 kW)

In the case of out-of-phase pulses for a 10 mm inter-wire distance, arc interruptions were verified in the trailing wire for all the conditions regardless of adding the Laser beam to the tandem GMAW process or not. The droplets were slightly less deviated than when using 'almost-in-phase' pulses and similar to the case of using out-of-phase pulses for 5 mm between the wires. The mean current and voltage values for the out-of-phase pulsing case are shown by Figure 5.28. As a comparison basis Figure 5.29 presents the mean current and voltage values for the weld beads produced using an inter-wire distance of 10 mm without using the Laser beam.

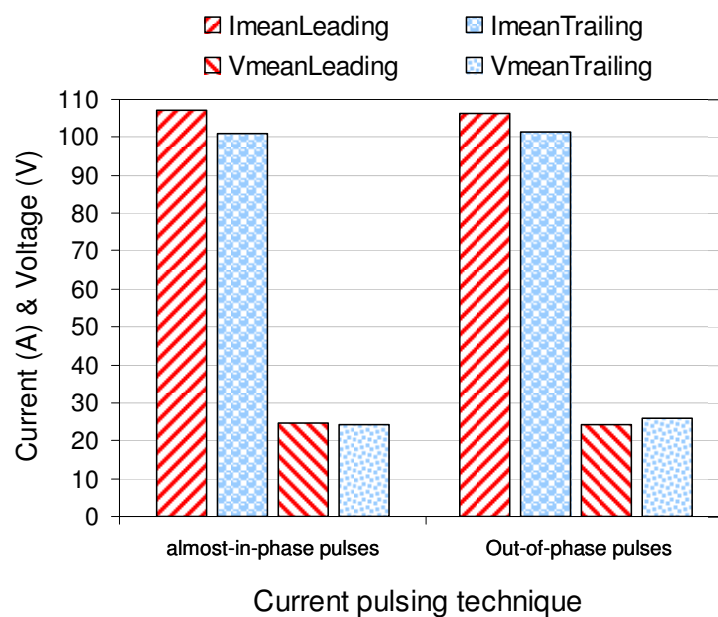


Figure 5.29: Mean current and mean voltage values for weld beads produced using an inter-wire distance of 10 mm without Laser beam

The effect of the Laser beam in the weld bead quality followed the tendency found for an inter-wire distance of 5 mm, that is, the Laser beam seemed to have a positive effect on this aspect, and the higher the Laser beam power the better (Figure 5.30). Despite the presence of arc interruptions in the trailing arc in the case of out-of-phase current pulses, the bead aspect did not differentiate significantly because the interruptions were not very long. The Laser beam helped to improve the appearance of the beads produced using such condition (probably by improving the wettability of the molten metal, resulting in a more uniform weld bead). This benefit of hybrid Laser - GMAW on the weld appearance was verified by Qin et al. (2007).

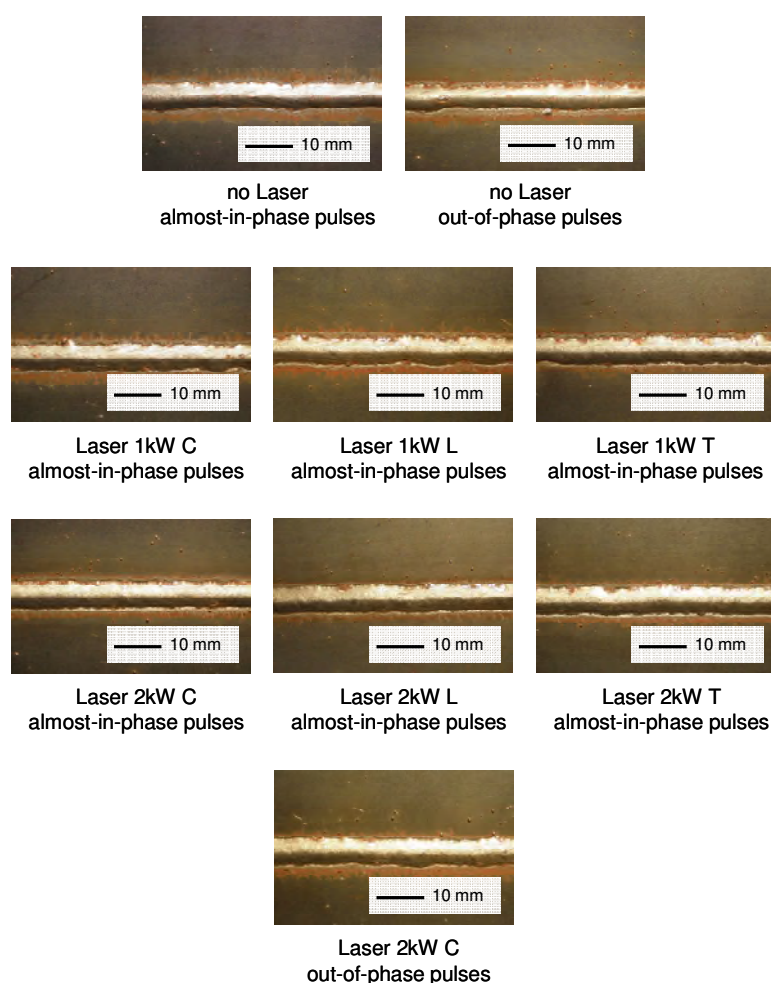


Figure 5.30: General aspect of weld beads produced with Laser - tandem pulsed GMAW using an inter-wire distance of 10 mm

A quick view in the droplets deviation was carried out following the same procedure used for an inter-wire distance of 5 mm. Figures 5.31 and 5.32 illustrate the droplets deviation in the leading and trailing wire respectively for 'almost-in-phase' and out-of-phase pulse conditions for 10 mm of inter-wire distance. The results for this measurement are congregated in Figure 5.33. As the inter-wire distance was increased, the deviation of the droplets when using 'almost-in-phase' pulses tended to decrease, with the droplets originated from the trailing arc being a little more deviated. The droplets deviation for the out-of-phase case practically did not change in comparison to the case of an inter-wire distance of only 5 mm with the same pulsing technique. The fact of having, in general, less deviation in the droplets was expected, since the magnetic force acting in the arcs and indirectly in the droplets decreases as the distance between the electrodes increases.

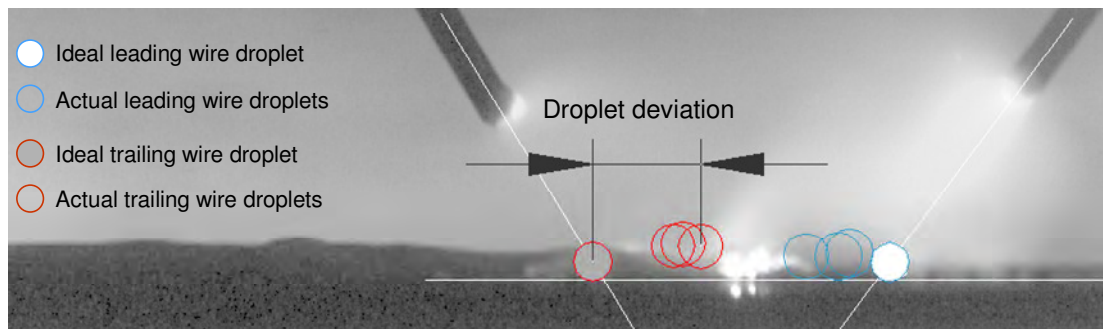


Figure 5.31: Droplet deviation for 'almost-in-phase' tandem pulsed GMAW
(inter-wire distance = 10 mm and central Laser beam power = 2 kW)

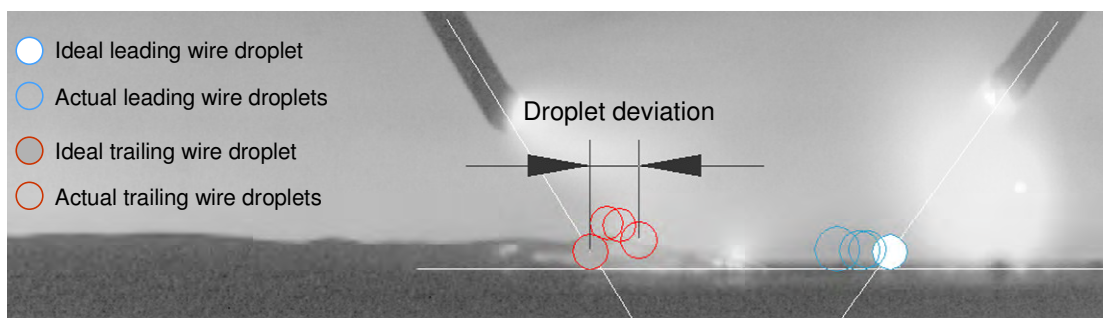


Figure 5.32: Droplet deviation for out-of-phase tandem pulsed GMAW
(inter-wire distance = 10 mm and central Laser beam power = 2 kW)

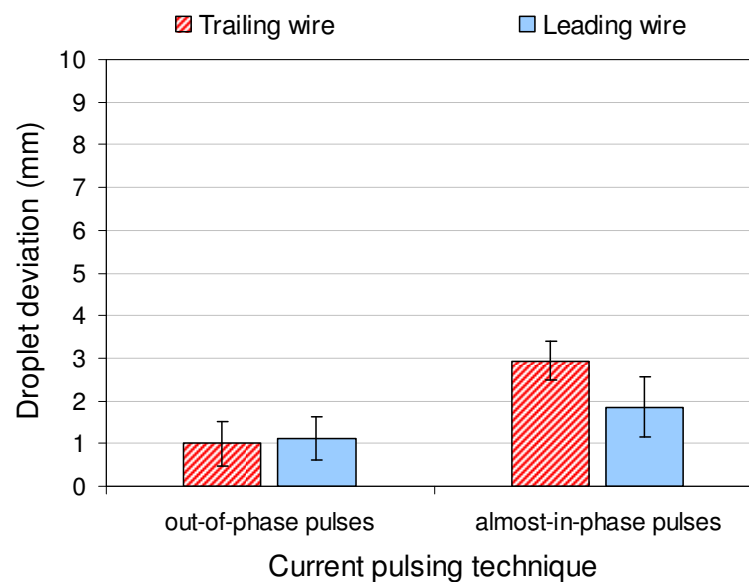


Figure 5.33: Droplet deviation in the leading and trailing arcs for different pulsing techniques
(inter-wire distance = 10 mm and central Laser beam power = 2 kW) (the trailing wire droplets actual deviation should be slightly longer since the droplets hit the weld pool slightly above the plate)

Inter-wire distance of 15 mm

As it was already verified in previous experiments using low levels of current for tandem pulsed GMAW, the use of 15 mm for the inter-wire distance caused interruptions in the trailing arc for both out-of-phase and 'almost-in-phase' pulsing techniques. Nevertheless, some observations regarding the effect of such inter-wire distance were still possible to be made. By observing Figure 5.34 it is possible to notice that 15 mm is out of the limit of the inter-wire distance range suitable for the level of welding travel speed used. The droplets from the leading wire tended to hit the plate too far away from the weld pool leading edge, forming a concentration of molten metal over the plate before being absorbed by the weld pool by means of surface tension forces. This phenomenon took place in a cyclical basis.

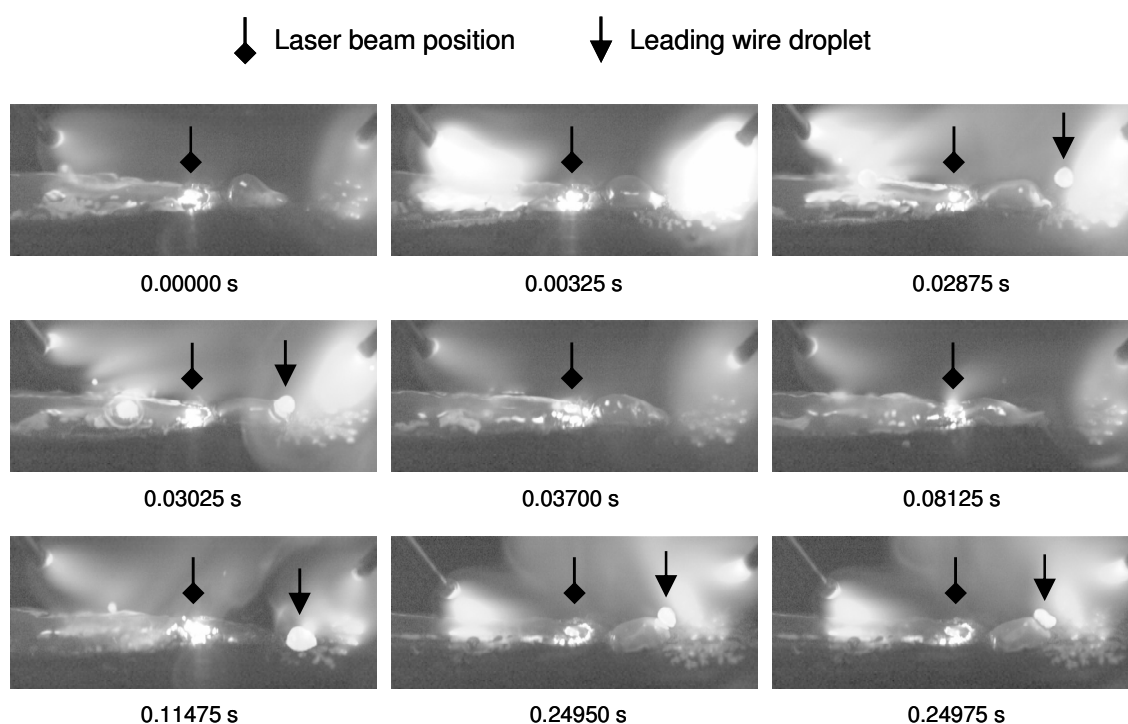


Figure 5.34: Sequence of images showing the tendency for accumulation of molten metal originated from the leading wire close to the leading edge of the weld pool ('almost-in-phase' pulses, Laser beam power = 2 kW and inter-wire distance = 15 mm)

The fact of using 15 mm between the wires and having such a high welding travel speed level combined with trailing arc interruptions deteriorated the aspect of the weld beads significantly (Figure 5.35). Without the Laser beam, porosity and lack of molten metal were largely present. However, by using the Laser beam the defects were minimized. As the Laser beam adds more heat to the weld pool, porosity is minimized (more time is allowed for gases

to escape before solidification) and more even weld beads produced (the wettability between the molten metal and the workpiece is improved).

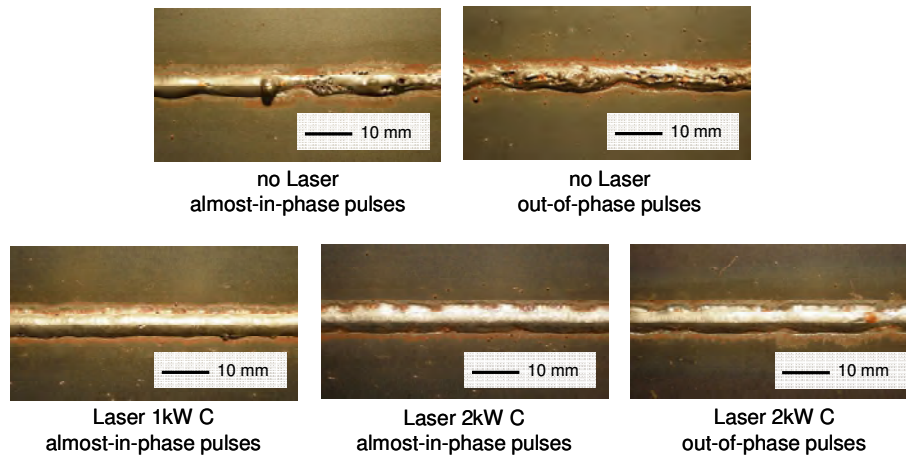


Figure 5.35: General aspect of weld beads produced with Laser - tandem pulsed GMAW using an inter-wire distance of 15 mm

Despite the presence of arc interruptions and the difficulty in achieving good weld bead visual quality for an inter-wire distance of 15 mm, a look was taken at the effect of utilizing such a distance between the wires on the deviation of the droplets. The same procedure used for an inter-wire distance of 5 mm and 10 mm was followed. Figures 5.36 and 5.37 show the droplets deviation in the leading and trailing wire respectively for 'almost-in-phase' and out-of-phase pulsing conditions for 15 mm of inter-wire distance. The results for the deviation measurements are showed in Figure 5.38. The tendency verified when increasing the inter-wire distance from 5 to 10 mm was confirmed for 15 mm, that is, the droplets originated from both leading and trailing wire had just a slight deviation towards the opposite arc. The deviation values were even similar for both 'almost-in-phase' and out-of-phase current pulses. In view of the poor results presented by the use of a 2 kW Laser beam located in the middle (centralized) of a 15 mm inter-wire distance, no more tests were carried out for such a distance between the wires.

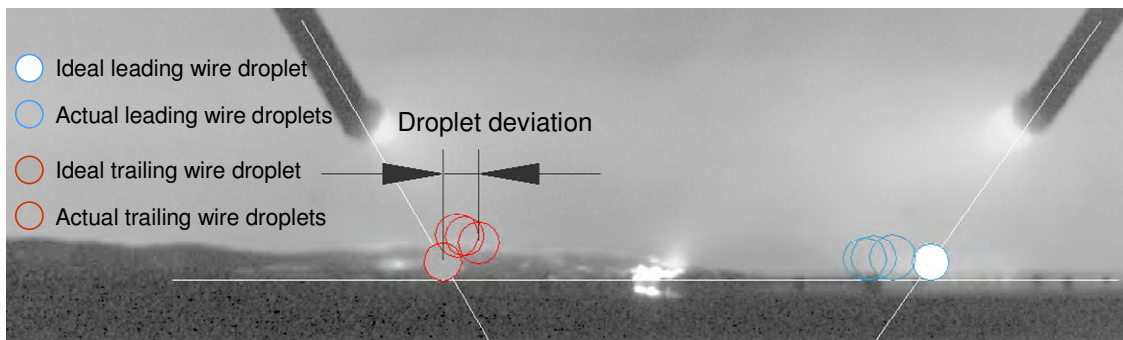


Figure 5.36: Droplet deviation for 'almost-in-phase' tandem pulsed GMAW
(inter-wire distance = 15 mm and central Laser beam power = 2 kW)

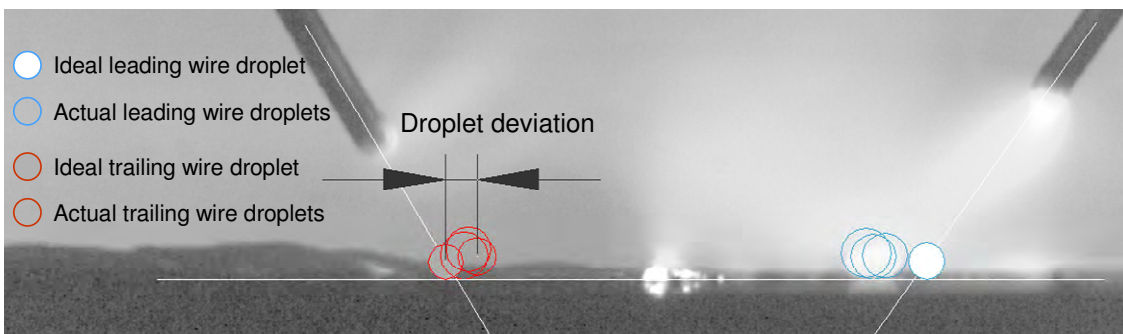


Figure 5.37: Droplet deviation for out-of-phase tandem pulsed GMAW
(inter-wire distance = 15 mm and central Laser beam power = 2 kW)

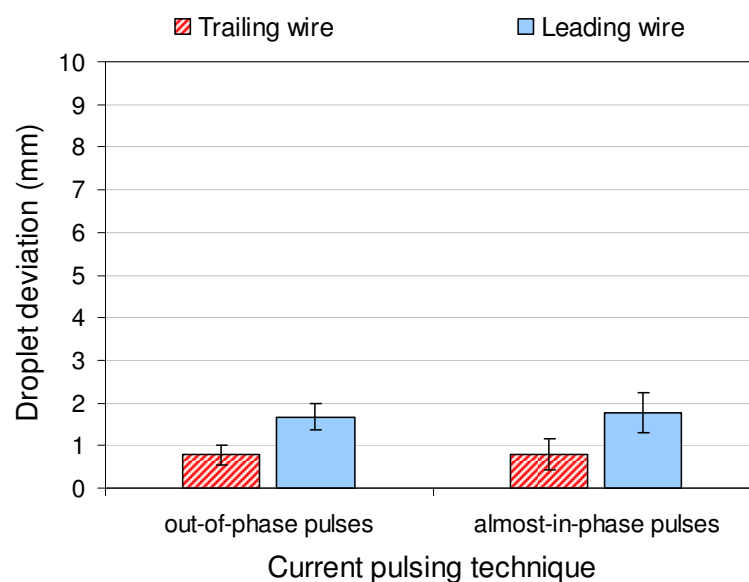


Figure 5.38: Droplet deviation in the leading and trailing arcs for different pulsing techniques
(inter-wire distance = 15 mm and central Laser beam power = 2 kW) (the trailing wire droplets actual deviation should be slightly longer since the droplets hit the weld pool slightly above the plate)

5.3.2 Weld bead characteristics

In order to assess the characteristics of the weld bead profile produced using the Hybrid Laser - tandem GMAW process, a series of tests was carried out using an inter-wire distance of 10 mm and the GMAW conditions showed in Tables 5.2 and 5.3 ('almost-in-phase' current pulses), since this combination provided the best results regarding the weld bead appearance. The welding travel speed, Laser beam position in relation to GMAW wires, and position of Laser beam focus in relation to the plate surface were varied and the influence on the weld bead profile was measured through the parameters showed by Figure 5.39. For each one of the conditions (bead produced) three cross sections were taken from the plate and suitable sample preparation was carried out (each section was polished, etched with NITAL 5 % and an image analyses software was used to measure the geometrical parameters). The final parameter value for each condition was, therefore, considered as the average of the parameter verified in 3 sections. Figure 5.40 gives a general idea of the weld bead profiles produced by the different combinations of tandem GMAW and Laser power levels.

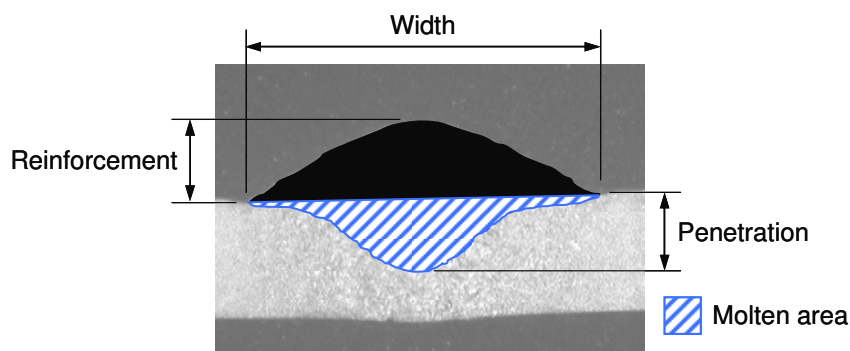


Figure 5.39: Weld bead geometrical parameters measured for evaluation of the hybrid Laser - tandem GMAW process

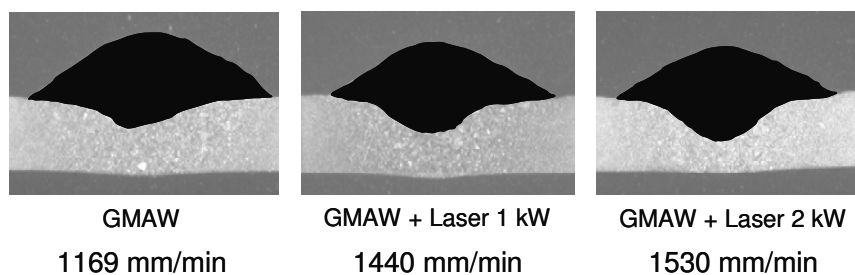


Figure 5.40: Example of weld bead profiles for tandem GMAW and hybrid Laser - tandem GMAW at 2 levels of Laser beam power (different welding travel speeds were used due to different operational ranges)

Influence of welding travel speed

Figure 5.41 shows the influence of the welding travel speed on the weld bead penetration. The travel speed range for each condition was chosen in order to assure a good visual aspect of the beads produced (regular shape and no burn-through). It is worth mentioning that in the case of the condition with Laser beam at 2 kW, the travel speed could be probably increased further. This was impractical as the limit of welding travel speed provided by the existing welding table system was reached. This fact also made impossible to use a higher Laser beam power (up to 3 kW available), which would be likely to increase the travel speed even more. Nevertheless, it is very clear that the fact of adding the Laser beam to the tandem GMAW process allows a reasonable increase in the welding travel speed level, still providing the same weld penetration. In reality the hybrid process allows a higher welding travel speed limit. According to Bagger and Olsen (2005), the reason for the high welding speed capability of Laser - GMAW seems to be the ability to avoid humping formation. Studies conducted by Cho and Farson (2007) also showed that the use of a Laser beam in front of the GMAW weld pool prevents the formation of humping.

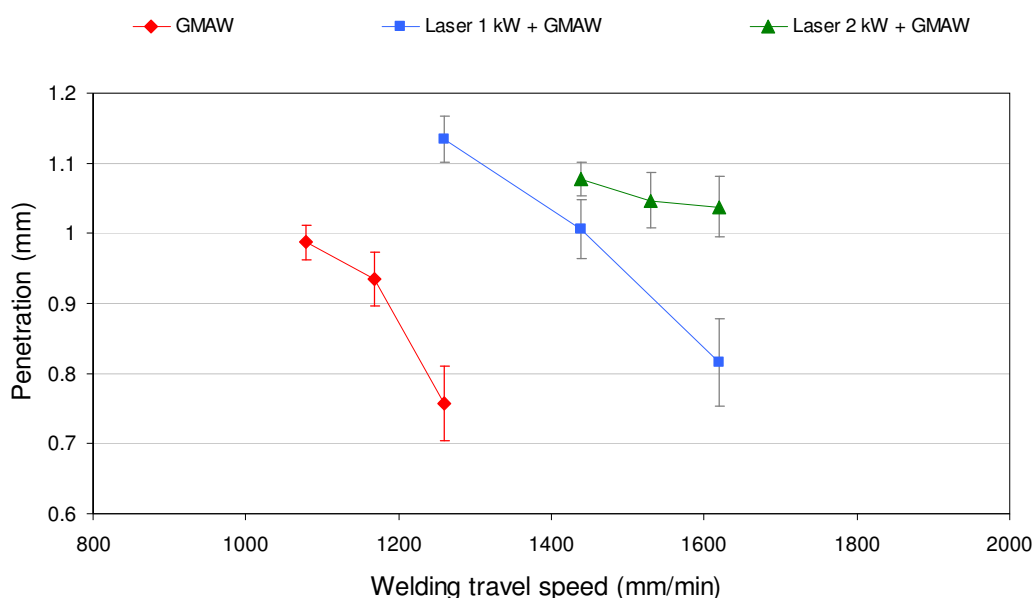


Figure 5.41: Influence of welding travel speed on weld bead penetration for tandem GMAW and hybrid Laser - tandem GMAW at 2 levels of Laser beam power (Laser beam centralized between the wires)

A similar effect took place in relation to the width of the weld beads. Figure 5.42 shows how the addition of an extra heat source (Laser beam) helps to achieve the same width at

higher welding travel speeds. This is likely to be due to the increase in the wetability of the deposited metal on the base metal, thanks to the extra heat provided by the Laser beam.

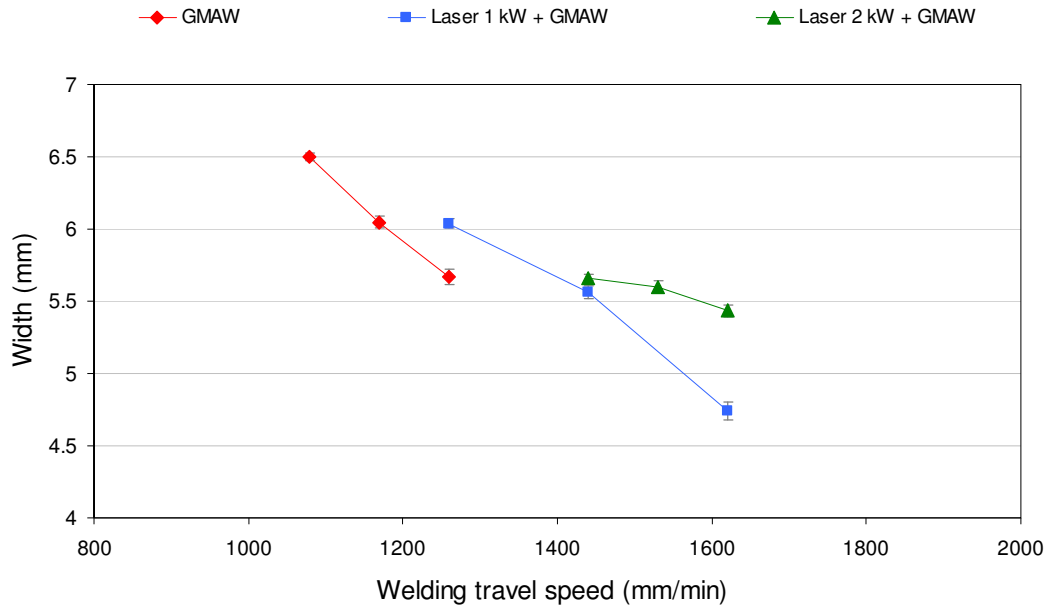


Figure 5.42: Influence of welding travel speed on weld bead width for tandem GMAW and hybrid Laser - tandem GMAW at 2 levels of Laser beam power (Laser beam centralized between the wires)

Figure 5.43 shows the effect already expected for the case of the weld bead reinforcement. As the weld width tended to increase by adding the Laser beam to the process, the reinforcement had to decrease, since the wire feed rate was kept constant throughout the tests.

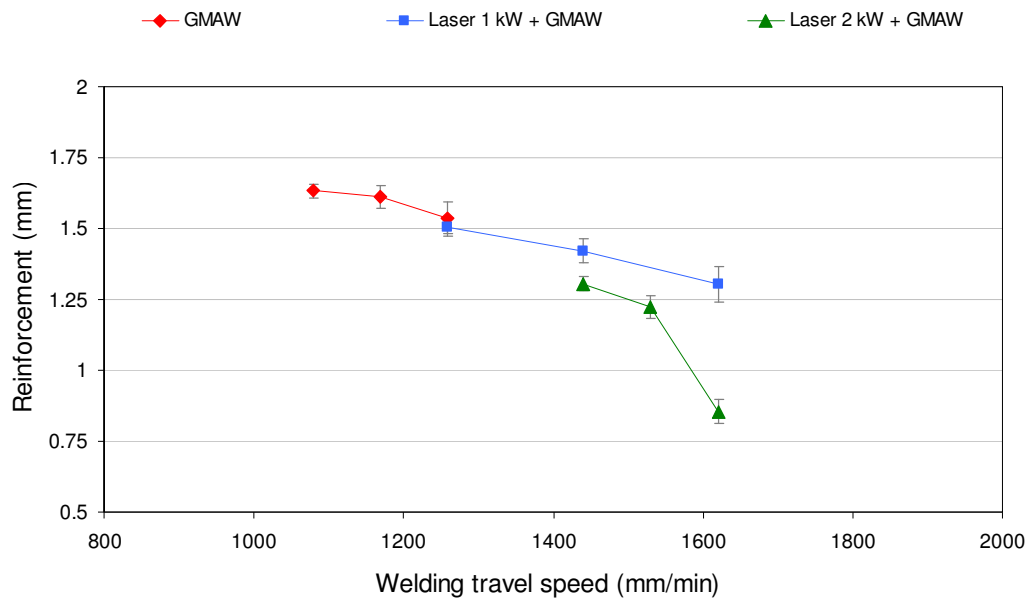


Figure 5.43: Influence of welding travel speed on weld bead reinforcement for tandem GMAW and hybrid Laser - tandem GMAW at 2 levels of Laser beam power (Laser beam centralized between the wires)

Figure 5.44 shows the influence of the welding travel speed on the base metal molten area. The result indicates that by combining the tandem GMAW process with the Laser process it is possible to keep the weld penetration profile even at higher travel speeds than those using only the tandem GMAW.

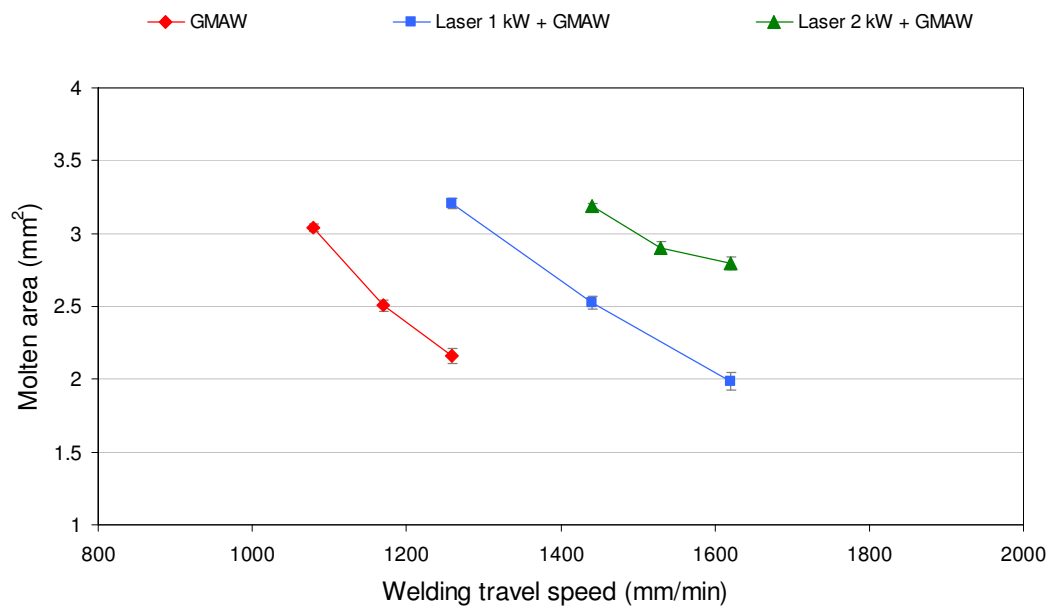


Figure 5.44: Influence of welding travel speed on base metal molten area for tandem GMAW and hybrid Laser - tandem GMAW at 2 levels of Laser beam power (Laser beam centralized between the wires)

Influence of Laser beam position

The position of incidence of the Laser beam was varied in accordance to Figure 5.9. According to Figure 5.45, the position of the Laser beam does not seem to affect the width or reinforcement of the weld bead. However, the penetration depth is significantly increased if the beam is placed centralised between the wires. The results show an increase around 50 % in penetration depth in relation to having the Laser beam closer to the trailing or leading wire. Figure 5.46 shows the influence of the position of the Laser beam on the base metal molten area. As the position of the Laser beam did not show a large effect on the weld width, the effect on the molten area is a direct consequence of the influence on the penetration depth. The molten area with the Laser beam centralised between the wires was around 50% higher than in the other positions. The Laser beam applied in the central position not only favoured beads with good appearance (previous results), but with high penetration depth as well.

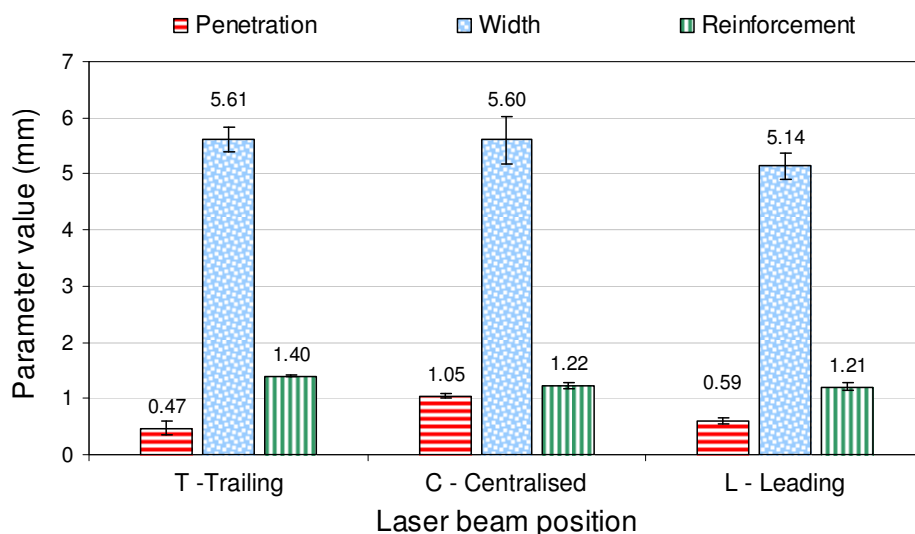


Figure 5.45: Influence of Laser beam incidence position on weld bead penetration, width and reinforcement for hybrid Laser - tandem GMAW (Laser beam power = 2 kW and Welding travel speed = 1530 mm/min)

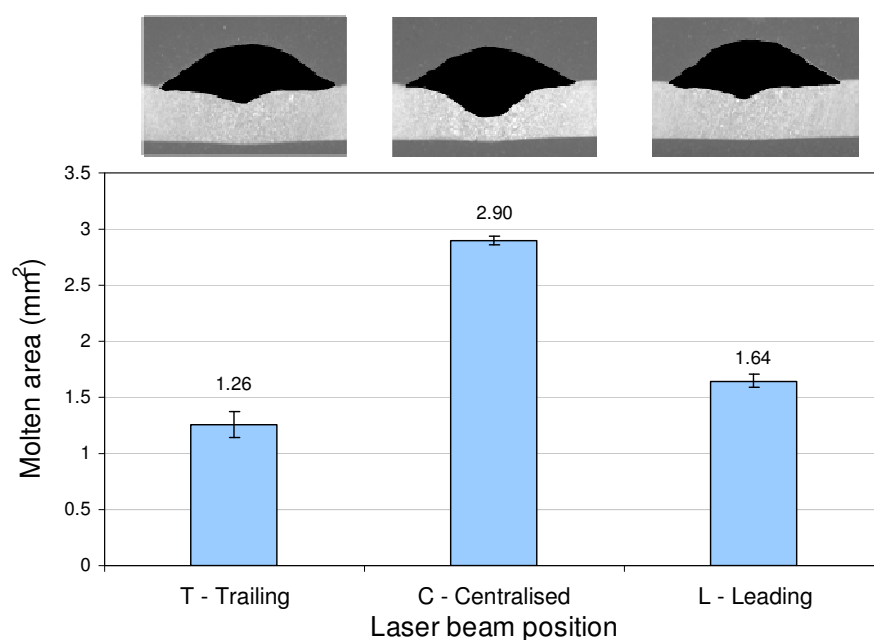


Figure 5.46: Influence of Laser beam position on base metal molten area for hybrid Laser - tandem GMAW (Laser beam power = 2 kW and Welding travel speed = 1530 mm/min)

It seems that the process becomes ‘less hybrid’ as the Laser beam is taken from the centre of the inter-wire distance (the situation for the Laser beam closer to the trailing wire is worse). This fact suggests that there is an optimum point to apply the Laser beam in the weld pool where the heat provided by the Laser is used more efficiently and the synergic effects between the Laser beam and the GMAW arcs are more pronounced. In somehow the Laser - tandem GMAW process behaves as the hybrid process using Laser and only one GMAW wire. According to Kim et al. (2006), a critical depth of molten material needs to be formed before being irradiated by the Laser beam in order to maximise the coupling effects of the respective heat inputs (LBW and GMAW).

Influence of Laser beam focus point

According to Figures 5.47 and 5.48, the position of the Laser beam focus point in relation to the plate surface did not show any major influence, neither in the penetration, width, reinforcement, nor in the base metal molten area. This fact is in disagreement to the statement provided by Duley (1999), which affirm that in LBW the Laser beam focal position should be below the material surface to achieve maximum penetration. This influence of the Laser beam focus point was verified also in hybrid process with GMAW (MATSUDA et al., 1988). This disagreement regarding the results may be due to the kind of Laser used, the presence of two arcs instead of one, etc. In the case of the kind of Laser, for example, the

optical system may be more prone to thermal deformation (CO_2 Laser, for instance) and the Laser beam focus point should be changed to compensate any discrepancy (CHEN; FANG; LI, 2004). The deformation tends to shorten the focus point distance. In this case, the Laser head should be put closer to the workpiece, which, in turn, means that the 'apparent focal point' should be displaced towards the workpiece (below the surface). This thermal deformation effect may be weak in the tests conducted as a Diode Laser system was used and also for the presence of two GMAW wires (no results available for comparison). The results might be also influenced by errors in defining the Laser beam focus point reference line (Figure 5.7).

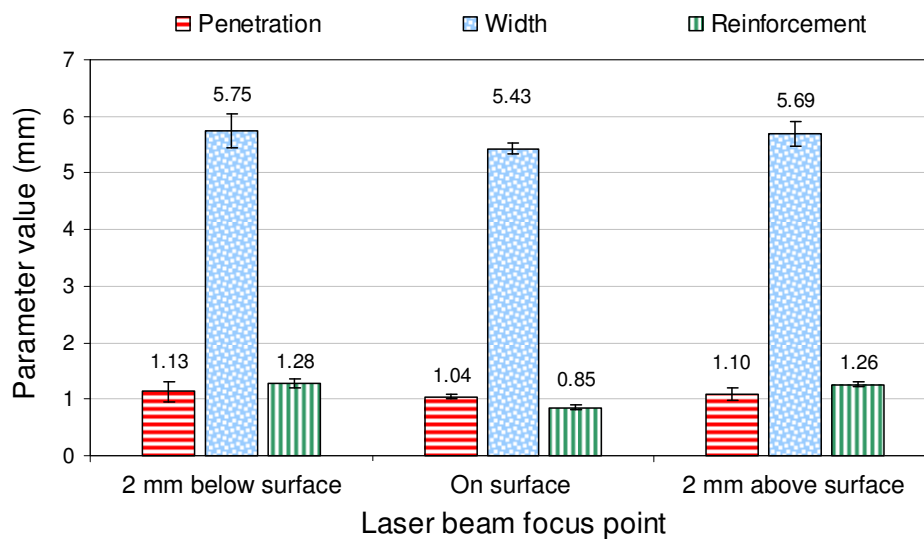


Figure 5.47: Influence of Laser beam focus point on weld bead penetration, width and reinforcement for hybrid Laser - tandem GMAW (Laser beam power = 2 kW, Laser beam centralized between the wires and welding travel speed = 1626 mm/min)

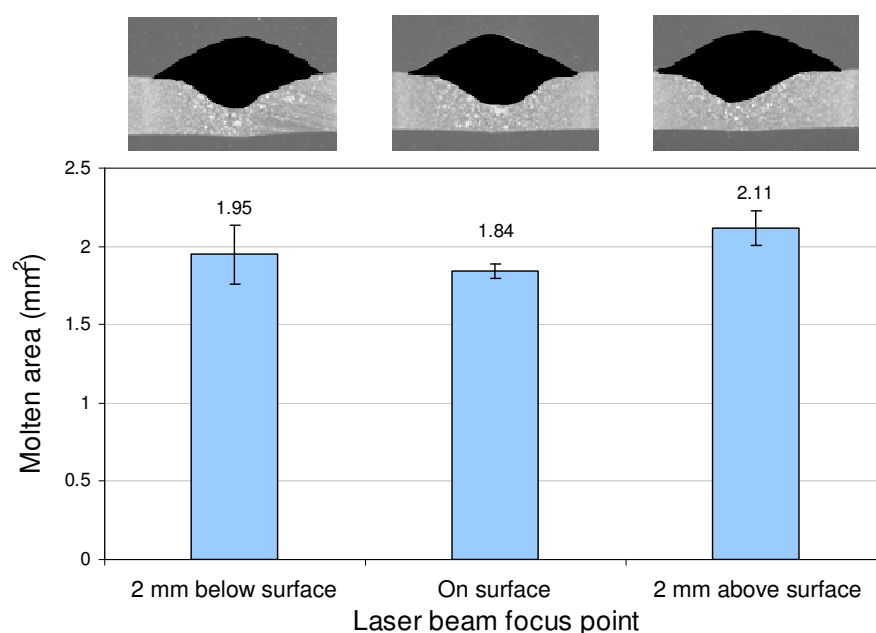


Figure 5.48: Influence of Laser beam focus point on base metal molten area for hybrid Laser - tandem GMAW (Laser beam power = 2 kW, Laser beam centralized between the wires and Welding travel speed = 1626 mm/min)

5.4 General Comments

- Regardless of welding with 'almost-in-phase' or out-of-phase current pulses for the tandem GMAW process, the Laser beam had a positive effect on the aspect of the weld beads produced (the higher the Laser beam power the better);
- The first trials indicated that the Laser beam is better used if located half way between the leading and trailing wire and an inter-wire distance of 10 mm promoted the best welding results under the conditions used;
- The hybrid process approach indicated to be able to increase significantly the maximum welding travel speed or penetration depth on bead on plate tests in comparison to tandem GMAW (pulsed mode);
- The position of the Laser beam focus point in relation to the plate surface did not affect the weld bead profile for the conditions used;
- Despite these positives conclusions, a more detailed investigation is essential in order to evaluate the process and its variables in joint situations, different levels of GMAW energy and transfer modes, higher Laser beam power levels, different materials and thickness, etc. A cost assessment is also suggested.

CHAPTER VI

STUDY ON THE EFFECT OF MAGNETIC FIELDS ON ARC STIFFNESS

This chapter presents an investigation on the influence of external magnetic fields on welding arcs aiming to prove they can be blown out by magnetic fields. An electromagnet is devised and, to simplify the tests, GTAW arcs are subjected to magnetic fields produced by this equipment. The influence of some welding parameters on the arc extinction is discussed.

6.1 Characteristics of Magnetic Attraction between Welding Arcs

Before discussing the interaction (deflection) taking place in the arcs in tandem GMAW, it is worth taking a brief look at the basic electromagnetism effect that governs the phenomenon. If an electrical charge travels inside a magnetic field, it will be subjected to a force with direction and magnitude described by Figure 6.1. Neither a stationary particle nor one moving parallel to the magnetic field lines will experience a force. The magnetic field alone cannot speed up or slow down a charged particle. It can and does, however, change the particle direction.

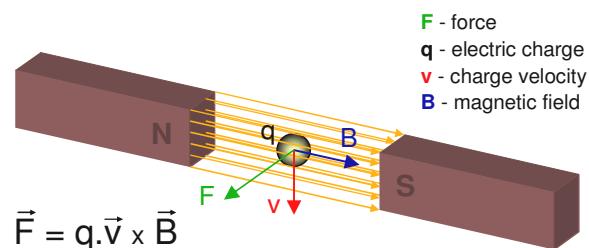


Figure 6.1: Force produced on a positive electrical charge moving through a magnetic field
(the force direction points the opposite way if the electrical charge is negative)

With the illustration provided by Figure 6.1 in mind, Figure 6.2 shows diagrammatically how two parallel welding arcs with current flowing in the same direction, that is, in the same

polarity, interact. The result of this interaction is the deflection of both arcs towards each other (attraction) (the arcs would repel each other if the current flowed in opposite directions in each one of them). From the electromagnetism laws, when an electrical current flows through a conductor, a magnetic field is generated. This is also true for the case of a welding arc (flux of electrons from the electrode to the work-piece or vice-versa). Let us take Figure 6.2 as a basis to the following discussion. In a simplified approach, as a current I_1 flows from the electrode 1 to the work-piece through an arc, a magnetic field B_1 is generated at a distance D from this arc according to Eq. (6.1).

$$B_1 = \frac{\mu_o \cdot I_1}{2\pi \cdot D} \quad (6.1)$$

In Eq. (6.1) μ_o is the free space magnetic permeability ($4\pi \times 10^{-7}$ Tm/A). According to the principles of electromagnetism, a linear electrical conductor in the presence of a magnetic field is subjected to a force proportional to the conducting length inside the magnetic field, to the electrical current flowing through this conductor and to the magnetic flux density. Therefore, in a simplified way, if a current I_2 is flowing from the electrode 2 to the work-piece through an arc of length L_{a2} , and this arc is in the presence of a magnetic field B_1 (produced by another arc), a force F_2 acting on this arc towards the other arc (perpendicular to the magnetic field flux B_1 and current flow I_2) is generated in accordance to Eq. (6.2).

$$F_2 = I_2 \cdot L_{a2} \cdot B_1 \quad (6.2)$$

As the magnetic field B_1 is produced by arc 1 (Eq. (6.1)), the force acting on arc 2 can be expressed as defined in Eq. (6.3).

$$F_2 = \frac{\mu_o \cdot I_1 \cdot I_2 \cdot L_{a2}}{2\pi \cdot D} \quad (6.3)$$

By analogy, the force generated on arc 1 (due to the magnetic field produced by arc 2) towards the arc 2 can be expressed as defined in Eq. (6.4).

$$F_1 = \frac{\mu_o \cdot I_1 \cdot I_2 \cdot L_{a1}}{2\pi \cdot D} \quad (6.4)$$

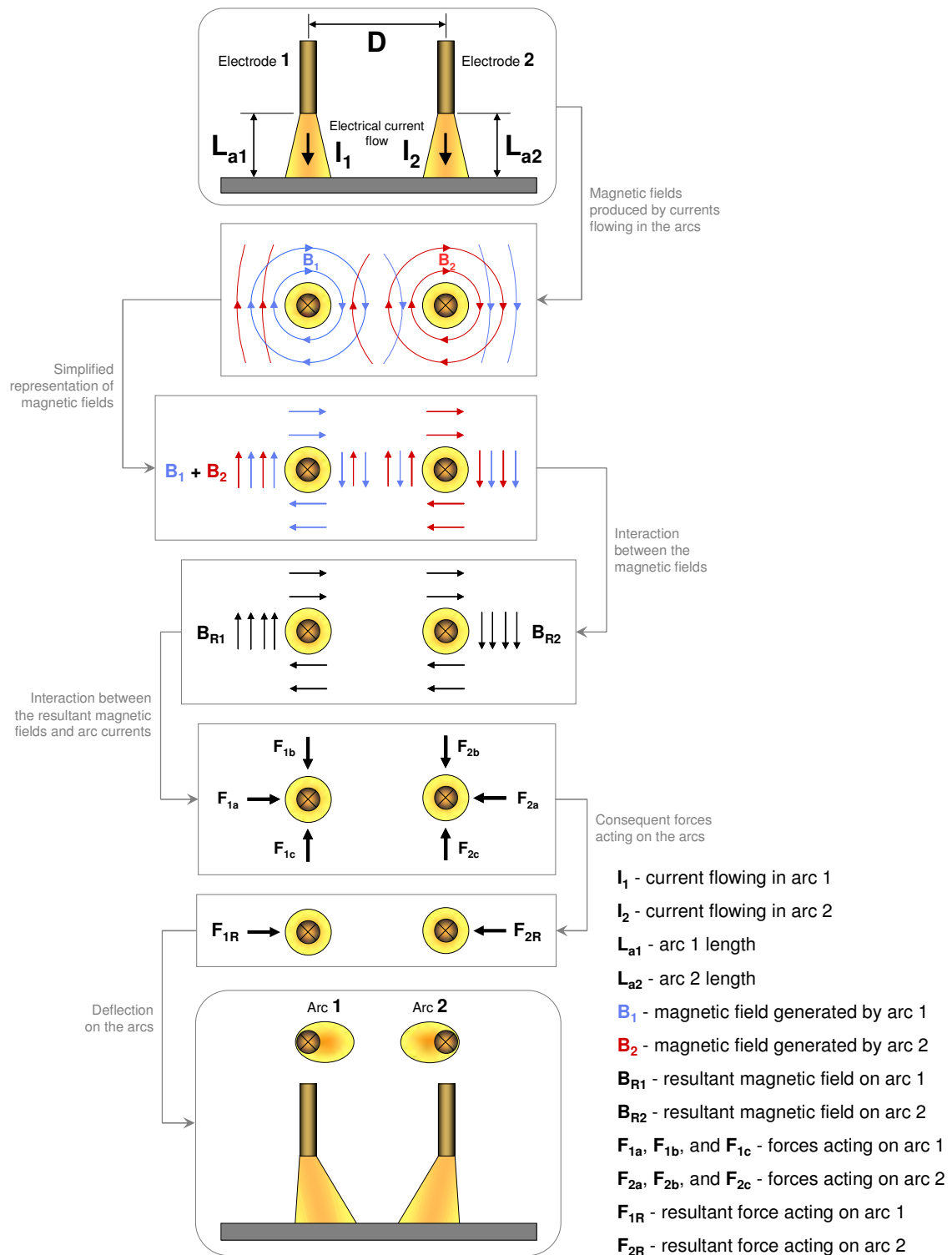


Figure 6.2: Diagrammatic explanation on how the deflection (attraction) of two parallel arcs and with current flowing in the same direction (same polarity) takes place (the arcs would repel each other if the current flowed in opposite directions in each one of them)

Taking the previous considerations into account, a deflection in a single arc can be obtained by applying an external magnetic field (to replace the other arc) as simply described

by Figure 6.3. Thus, following the same previous simplifications, if a current I is flowing from the electrode to the work-piece through an arc of length L_a and this arc is in the presence of a magnetic field B_E , a force F acting on the arc (perpendicular to the magnetic field flux B_E and current flow I) is generated in accordance to Eq. (6.5).

$$F = I \cdot L_a \cdot B_E \quad (6.5)$$

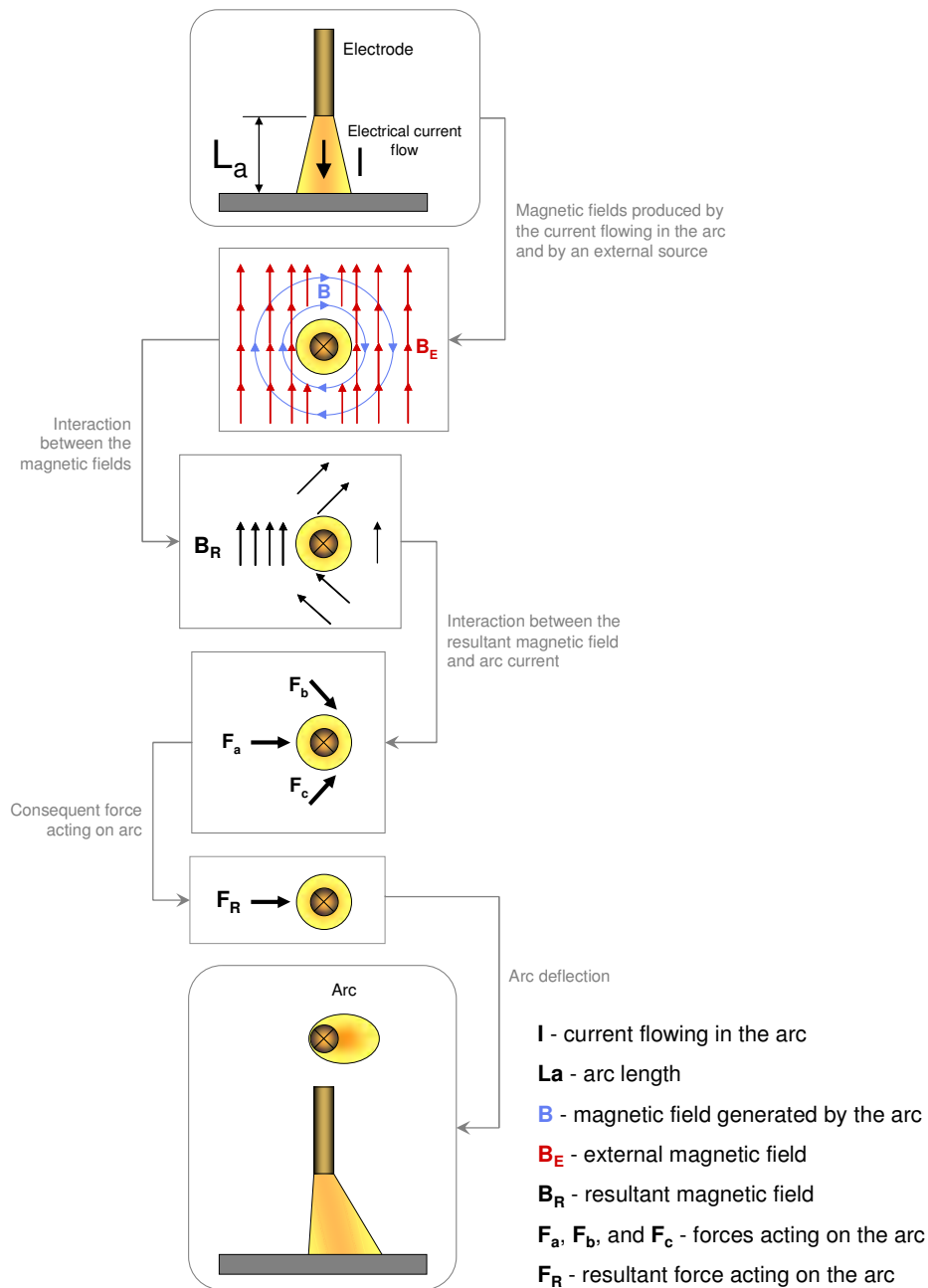


Figure 6.3: Diagrammatic explanation on how the deflection of an arc in the presence of an external magnetic field takes place

6.2 Electromagnet Design

When the interaction (attraction) between two arcs takes place in tandem GMAW is hard to distinguish and correlate a phenomenon to a unique cause, since a lot of variables and possible causes are often acting at the same time and are linked to each other. When the pulsed current mode is used, for instance, the magnetic field generated by the arcs and their stiffness's are variable, their sizes change and so on. In order to verify if the magnetic field generated by one arc can be responsible for blowing out the other arc in tandem GMAW, a simplified approach to the problem is proposed. The idea is to use a GTAW arc in a constant current mode (easier to use and control), apply a sudden external magnetic field to this arc and verify the resistance offered by this arc to the blowing out process. By this approach, the influence of variables like welding current level, arc length, electrode angle (trailing or pushing the weld pool), high-frequency pulsing, etc., on the arc resistance to extinction can be promptly verified.

In order to generate an external magnetic field to replace the magnetic effect caused by one arc and avoid any other influence that this arc would have on the other arc, an electromagnet was devised. A coil from a commercial contactor (electromagnetic switching device) was used and the core was built by stacking thin sheets of electrical steel (high permeability and low hysteresis) together using anaerobic glue. The core was extended to keep the density of magnetic flux high even in a point distant from the coil. A voltage source (DC) was used to provide the current necessary to produce the magnetic field. Figure 6.4 shows the electromagnet built with one coil and one core and the respective magnetic field lines produced in a vertical and in a horizontal plane. The magnetic field lines were traced by cast iron chips on a white paper. As noticed, the magnetic field lines were quite deviated as soon as they left the core, resulting in a step reduction of magnetic flux density.

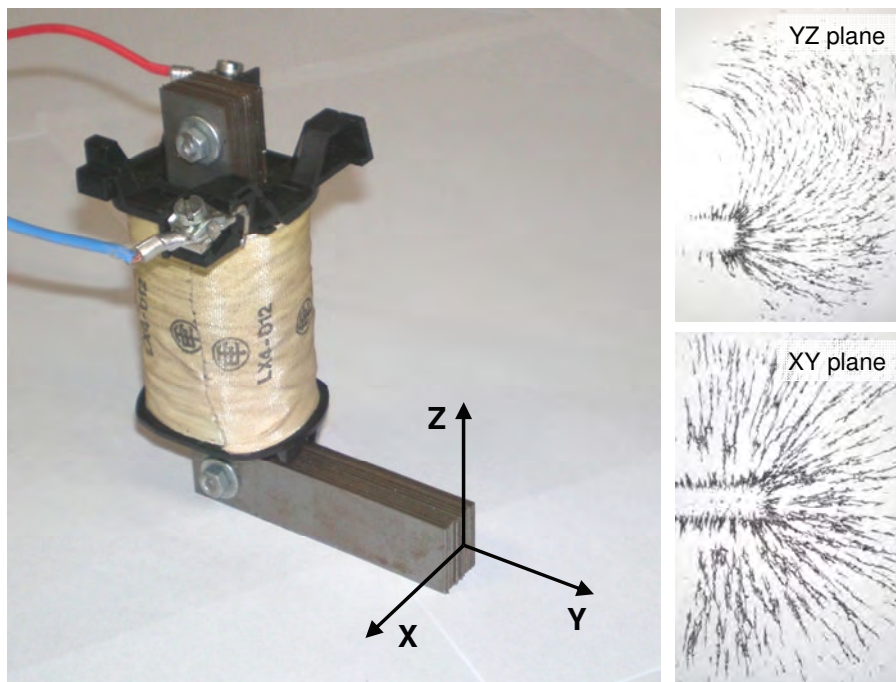


Figure 6.4: Distribution of magnetic field lines around the electromagnet formed by one coil and one extended core

In order to increase the concentration of magnetic field lines (magnetic flux density) in the region close to the core edge (place where the arc must be present to be deflected), another electromagnet, identical to the previously devised, was built and connected in series with the previous one forming a new electromagnet. Figure 6.5 and Figure 6.6 illustrate the idea behind the new electromagnet. Now the magnetic field produced between the electromagnet poles will be stronger and more concentrated. Figure 6.7 shows the magnetic field lines produced by the new electromagnet in a vertical and in a horizontal plane. The new approach really increased the density of magnetic flux in the region between the poles.

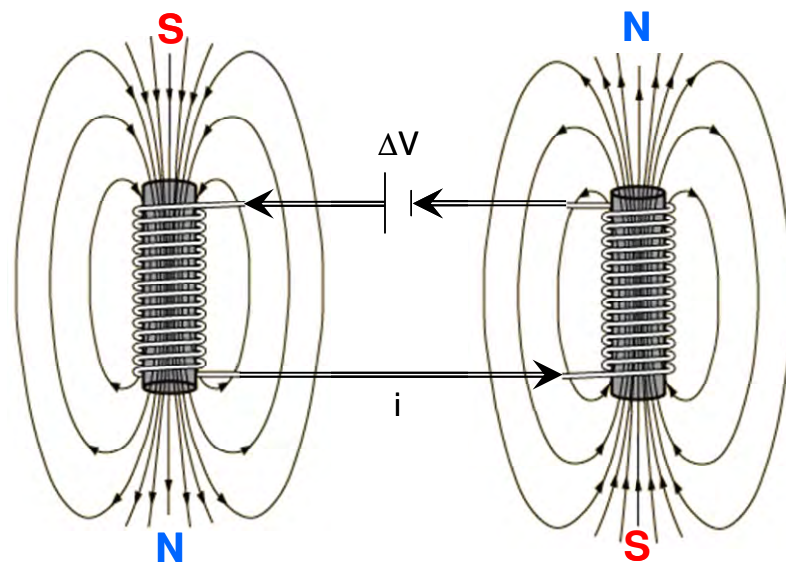


Figure 6.5: Illustration of magnetic field lines produced by two electromagnets connected in series

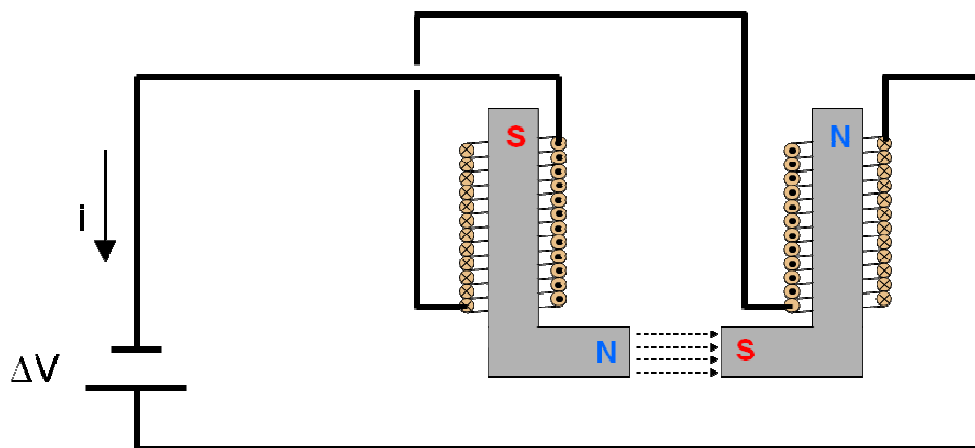


Figure 6.6: Electrical diagram of the electromagnet formed by two coils and two extended cores (connection in series)

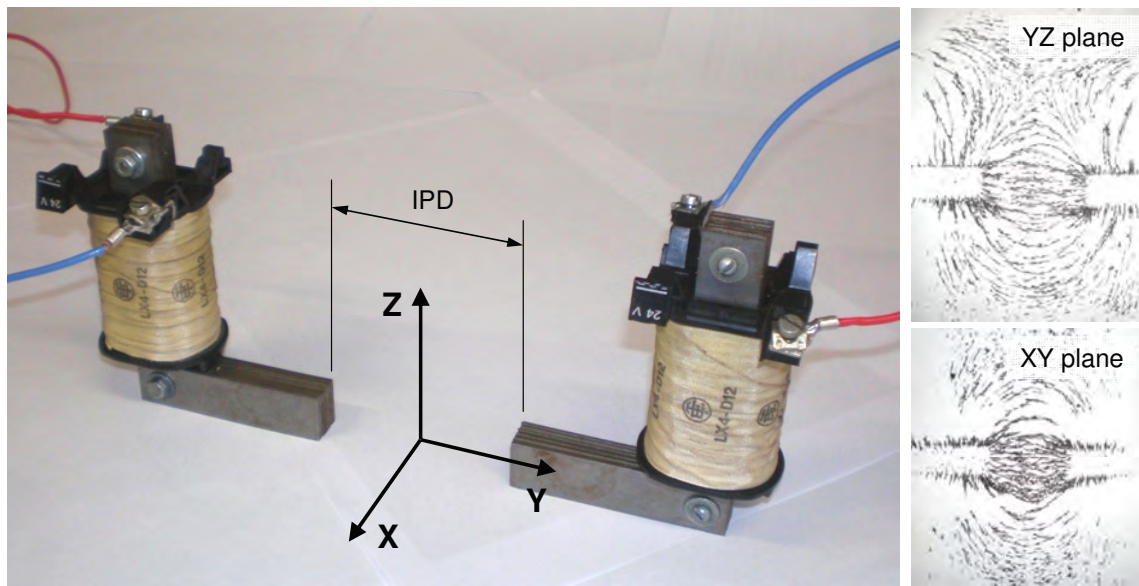


Figure 6.7: Distribution of magnetic field lines around the electromagnet formed by two coils and two extended cores (IPD = inter-pole distance)

Before taking any GTAW arc to the influence of the magnetic field to verify the effects of any parameter, the magnetic field must be characterized and quantified. In order to measure the magnetic flux density produced by the electromagnet, a PHYWE Teslameter (Figure 6.8) was used. Figure 6.9 shows how the magnetic flux density varies if the distance between the electromagnet poles is changed. Two levels of voltage (current) were used; the maximum supported by the coils (48 V or 0.33 A) and an intermediate value. The magnetic flux density decreased as the distance between the poles was increased and the fall in its value was quite pronounced for the range with shorter inter-pole distances. Figure 6.10 shows qualitatively the effect caused by increasing the distance between the electromagnet poles.



Figure 6.8: Teslameter used to measure the electromagnet magnetic flux density

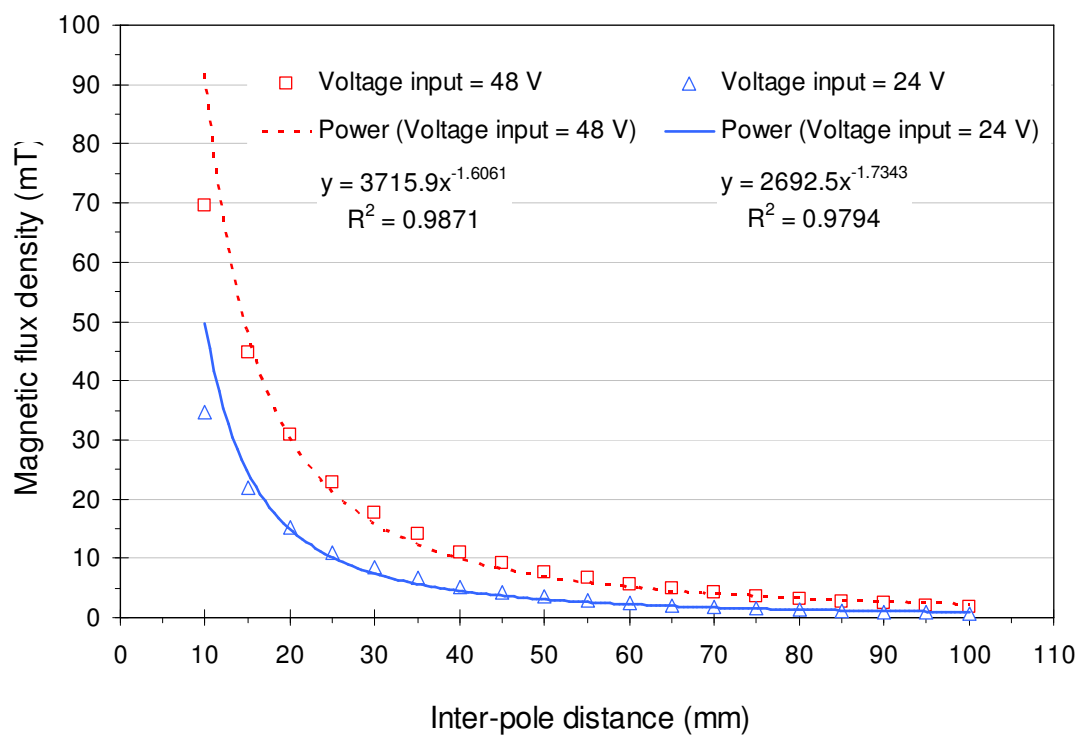


Figure 6.9: Magnetic flux density measured at central point of IPD (0,0,0) for various inter-pole distances

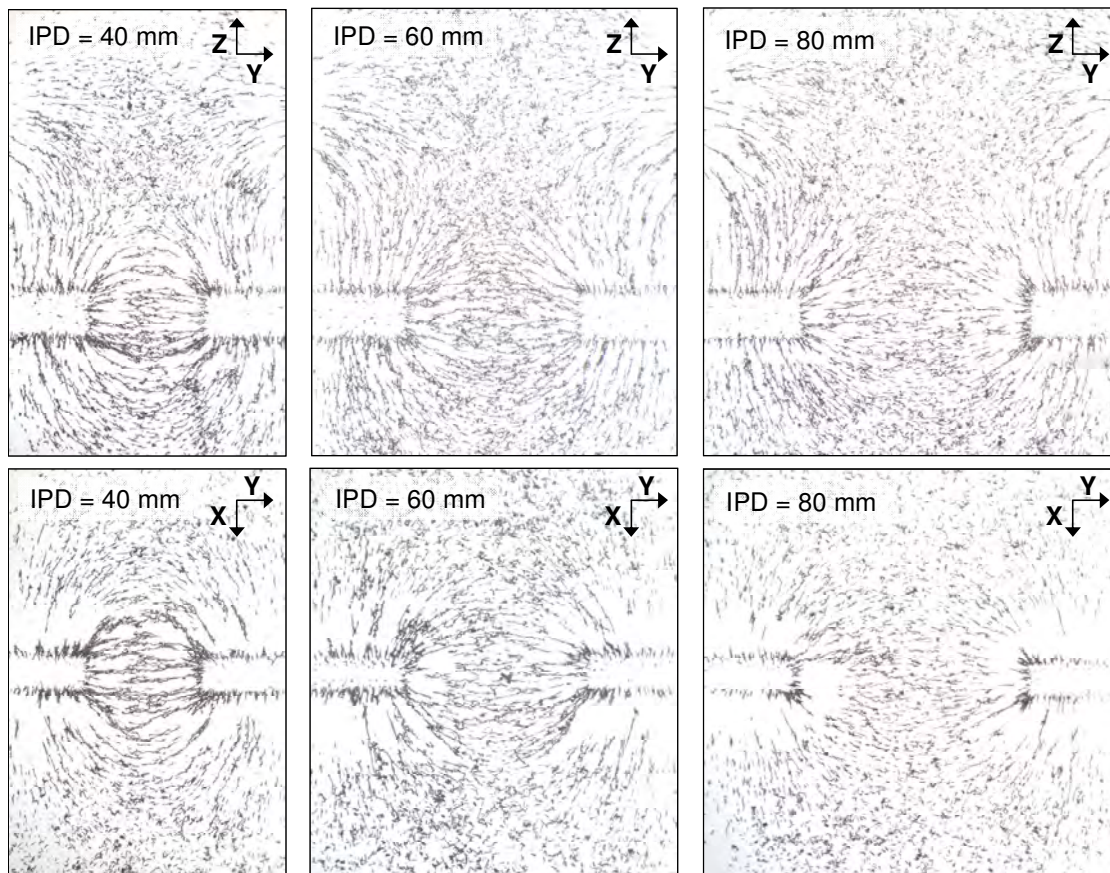


Figure 6.10: Distribution of magnetic field lines for different IPD values (electromagnet voltage input = 48 V)

In order to assess the magnetic field between the poles along different directions, the inter-pole distance of 50 mm was selected. Distances around this value seem to be enough to avoid overheating of the cores extensions during the welding tests, which could lead to the Curie temperature (loss of magnetic property). According to Figure 6.9, the value of the magnetic flux density at the central point of the inter-pole distance of 50 mm is around 8 mT (80 Gauss). Considering the tandem GMAW case, through simplifications and using Eq. (6.1), a current pulse of 350 A in the leading arc generates a magnetic flux density of 7 mT (70 Gauss) at a trailing arc 10 mm distant. These conditions are likely to have caused the trailing arc extinction when this arc was in a 50 A current. Therefore, inter-pole distances around 50 mm seem to be able to provide the magnitude of the adverse magnetic effect caused by another arc. Just as a comparison basis, magnetic fields up to 5 mT (50 Gauss) have been used in magnetic arc oscillation studies. Kang and Na (2002), for instance, used magnetic flux densities up to this level in their experiments and did not mention any adverse arc disturbances.

Figure 6.11 and Figure 6.12 present, respectively, the distribution of magnetic field lines on the YZ and XY plane for an inter-pole distance of 50 mm. The points for magnetic flux density measurements are indicated as well. In each direction the voltage was applied in two levels (maximum allowed and intermediate), without the welding sample around and with the welding sample placed 12 mm below the poles to check any additional effect. This distance (12 mm) was chosen to allow measurements of magnetic flux density below the poles (negative Z direction), that is, to put the magnetic field sensor in this region. Figure 6.13 shows the welding sample dimensions and Figure 6.14 shows how the welding sample was put below the electromagnet.

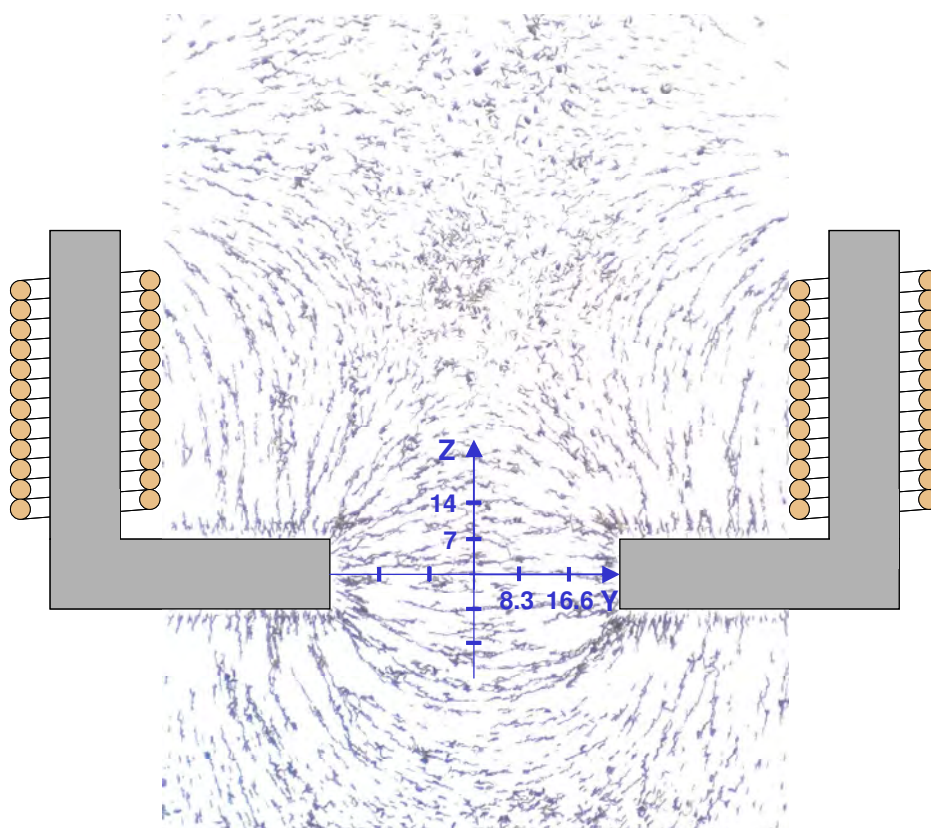


Figure 6.11: Distribution of magnetic field lines on the YZ plane for an IPD of 50 mm
(electromagnet voltage input = 48 V)

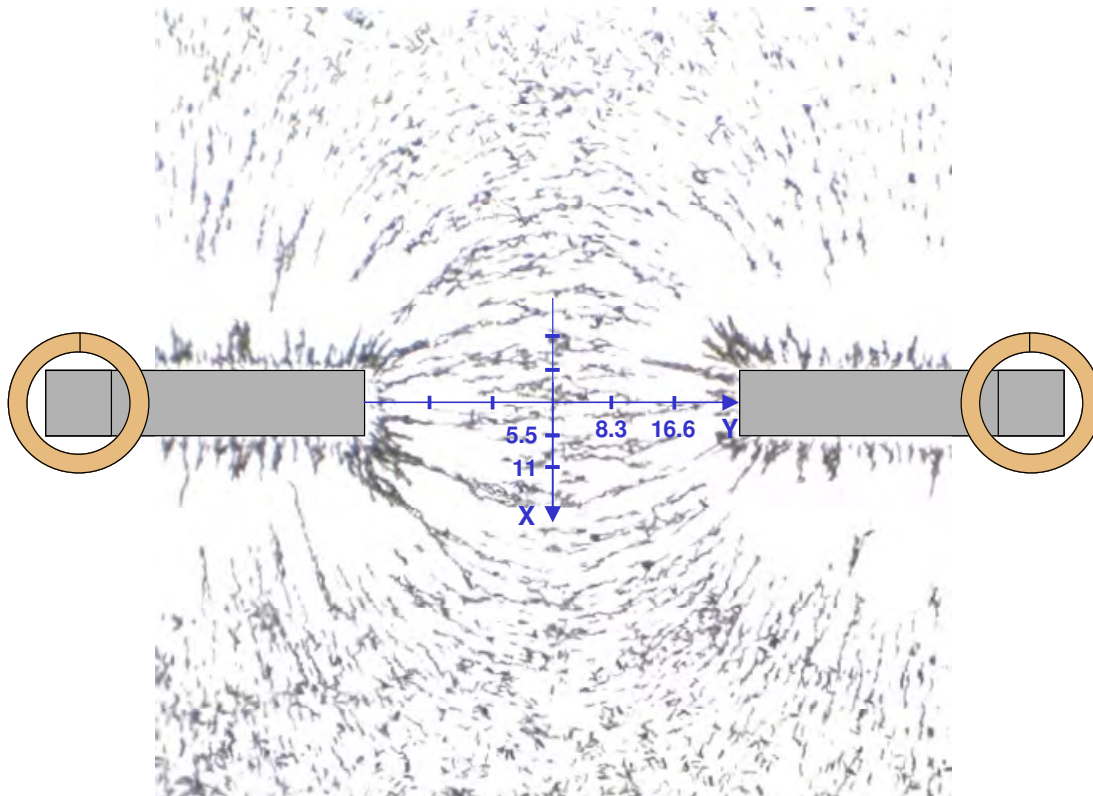


Figure 6.12: Distribution of magnetic field lines on the XY plane for an IPD of 50 mm (electromagnet voltage input = 48 V)

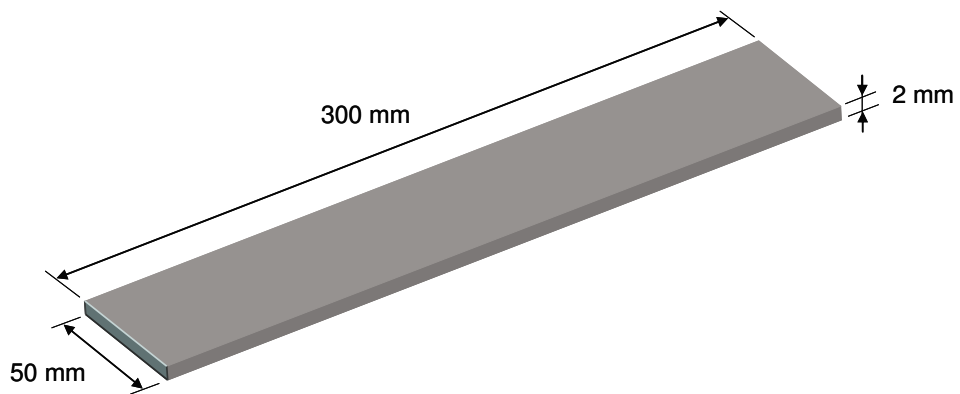


Figure 6.13: Welding sample (low carbon steel) used for the arc stiffness assessment

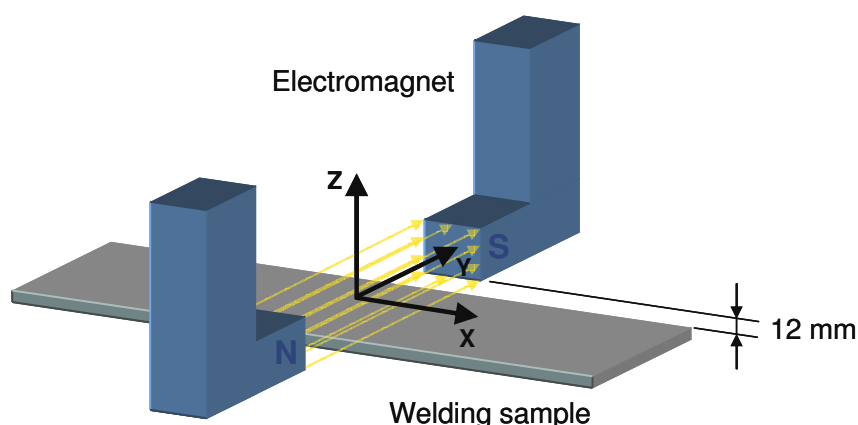


Figure 6.14: Welding sample placed below the electromagnet

Figures 6.15, 6.16 and 6.17 show, respectively, the magnetic flux density measurements carried out along the X, Y and Z directions. As the conditions (with and without welding sample) are symmetrical for the X and Y directions, for these cases the magnetic flux density was measured in one way (positive side) and mirrored to the other way (negative side). In the Z direction case, there is symmetry without the welding sample, which allowed the mirror approach to be used in the measurements. However, when the welding sample is put below the electromagnet poles there is no symmetry of conditions along the Z direction. In this case, actual measurements were conducted throughout the Z direction.

The magnetic flux density falls as the distance along the direction X is increased (Figure 6.15). For high levels of voltage input the fall is attenuated. This tendency was verified with or without the welding sample below the electromagnet. When the welding sample was placed below the electromagnet, the values of magnetic flux density had a significant fall. This effect was expected since the welding sample is ferromagnetic and has a magnetic permeability much higher than the air. The magnetic flux 'prefers' to travel through the sample instead of through the air (between the poles). Therefore, the magnetic flux was deviated downwards, which decreased its value throughout the X direction.

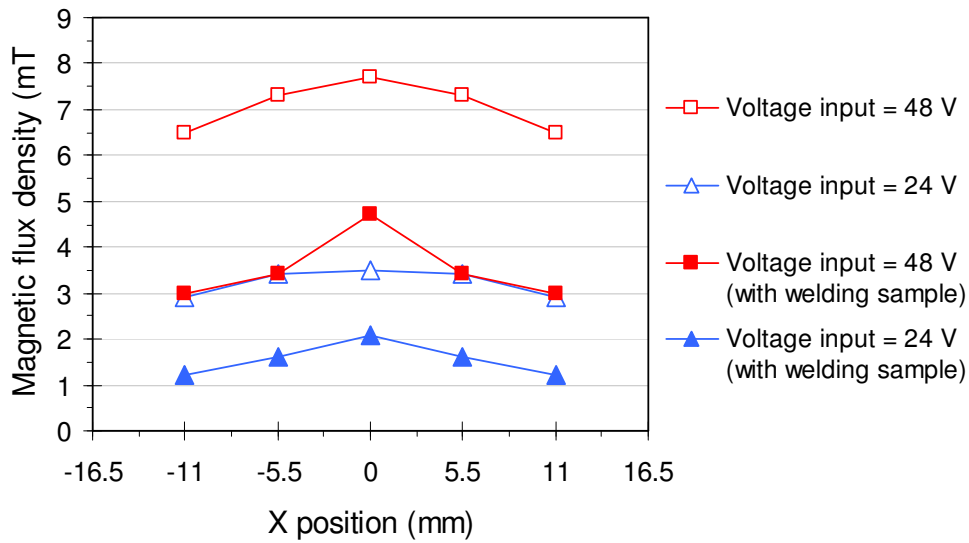


Figure 6.15: Magnetic flux density along the X direction ($Y = 0$, $Z = 0$ e $IPD = 50$ mm)

The magnetic flux density increases as the distance along the direction Y is increased (Figure 6.16), that is, at points closer to the electromagnet poles. For high levels of voltage input the increase is more intense. This tendency was noticed with or without the welding sample below the electromagnet. As expected, when the welding sample was placed below the electromagnet, the magnetic flux was deviated downwards, which decreased its value throughout the Y direction. The values of magnetic flux density close to the electromagnet poles were very similar for each of the voltage input values used regardless of placing the welding sample below the electromagnet or not. This fact indicates that the magnetic field flows preferably through the cores even with the welding sample below them. As soon as the magnetic field reaches the edge of the cores it started to be deviated downwards.

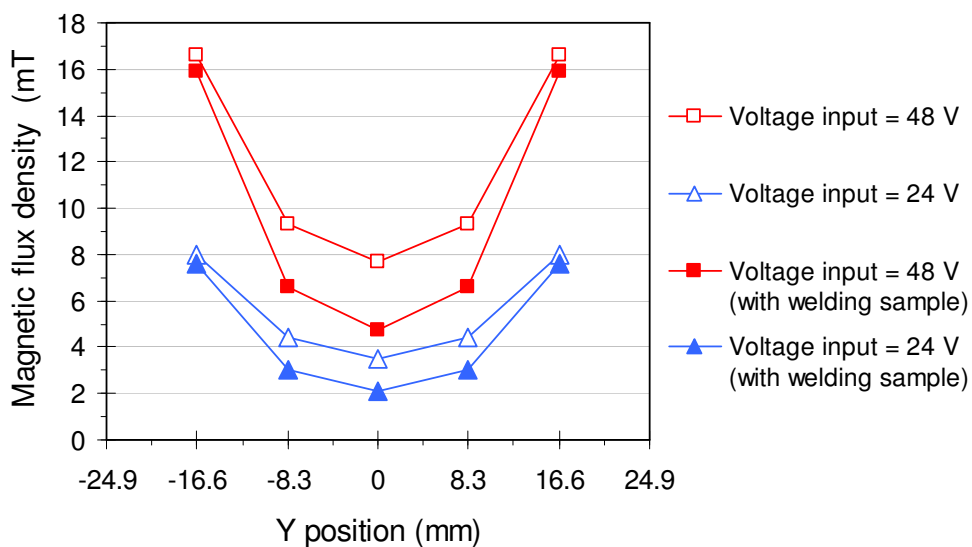


Figure 6.16: Magnetic flux density along the Y direction ($X = 0$, $Z = 0$ e $IPD = 50$ mm)

The magnetic flux density decreases as the distance along the direction Z is increased (Figure 6.17). For high levels of coil current the decrease is more intense. This tendency was detected with or without the welding sample below the electromagnet. As expected, when the welding sample was placed below the electromagnet, the magnetic flux was deviated downwards, which remarkably changed its value throughout the Z direction. The magnetic flux density had a pronounced fall at the edge of the electromagnet low level. This fact emphasises the deflection in the external magnetic field when the welding sample is present. In the situation with the welding sample bellow the electromagnet, the magnetic flux density was not measured at lower points due to physical impediments (welding sample position and probe size).

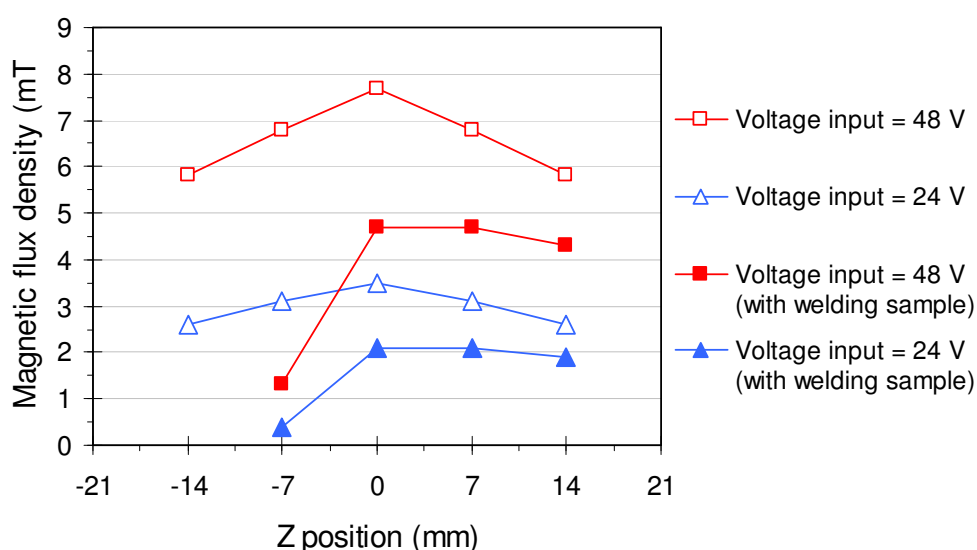


Figure 6.17: Magnetic flux density along the Z direction ($X = 0$, $Y = 0$ e IPD = 50 mm)

As discussed above, the magnetic field profile generated by the electromagnet is not so simple. As a consequence, any attempt to precisely quantify the arc resistance to extinction by means of the magnetic force would be very difficult to be conducted, since the magnetic field actually acting on the arc is hard to be estimated. As the arc is deflected by the magnetic force, the magnetic field acting on it also changes. The difficulties are even worsened if the welding environment influence is considered. Factors like different magnetic permeability, welding sample presence, etc., certainly change the actual magnetic field that acts on the arc, not to mention the interaction between the arc-induced magnetic field and the external magnetic field. For all these reasons, a qualitative approach for the arc resistance to extinction is proposed instead. The idea is to show the tendency of occurrence of a phenomenon (arc extinction in the presence of a magnetic field) and not to quantify the phenomenon. Thus, to simplify the analyses, the magnetic field acting on the arc will be

considered to be the value at the centre of the inter-pole distance measured in the air and with the welding sample placed 2 mm below the electromagnet. Thus, the magnetic flux density responsible for extinguishing the arc will be considered as a measure of arc stiffness and could be called the arc resistance to extinction; for a given welding condition, the higher the magnetic flux density to extinguish the arc, the higher the arc stiffness (arc resistance to extinction). Then, the influence of variables like welding current, arc length, etc., on the arc resistance to extinction will be qualitatively evaluated.

Figure 6.18 shows the relationship between the magnetic flux density and the electromagnet voltage input for different values of inter-pole distance. As expected, the relationship is linear and no saturation (magnetic flux density constant as the voltage, and consequent coil current, is increased) was observed. The effect of reduction in the magnetic flux density as the welding sample (plate) is placed close to the electromagnet is verified.

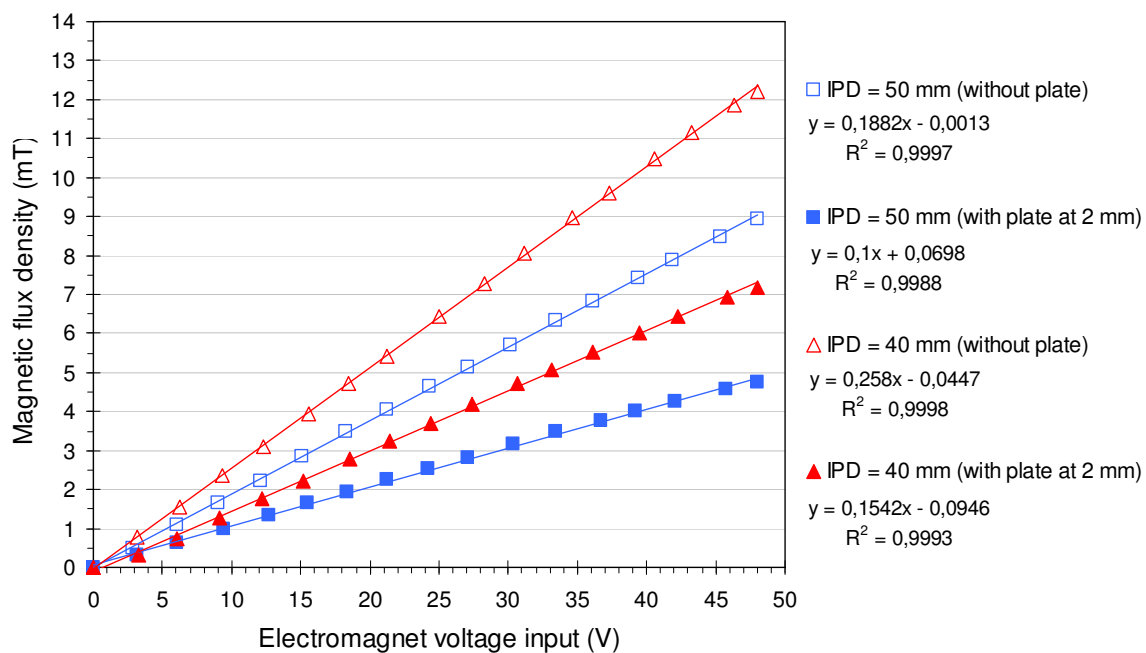


Figure 6.18: Magnetic flux density versus electromagnet voltage input (magnetic flux density measured at point 0,0,0 for different IPD values; without the welding sample and with the sample placed 2 mm below the electromagnet)

6.3 Tests with GTAW Arcs

In order to provide a sudden rise of magnetic field (similar to the situation found in tandem pulsed GMAW) and assess the resistance to extinction of DCEN (direct current with electrode in negative polarity) GTAW arcs, a variable DC voltage source (layout at Appendix 7) was built to be connected with the electromagnet and generate the current needed in the

coils. This voltage source allows continuous variation of the voltage input (up to 48 V) in the electromagnet, that is, variation of the current in the coils, which allows the magnetic flux density setting. Furthermore, it features a trigger (switch) to suddenly release the voltage (coil current), consequently the magnetic flux density. For instance, Figure 6.19 shows the raise in the magnetic flux density (calculated based on Figure 6.18) when voltage (current) is suddenly applied on the electromagnet (IPD = 40 mm with welding sample).

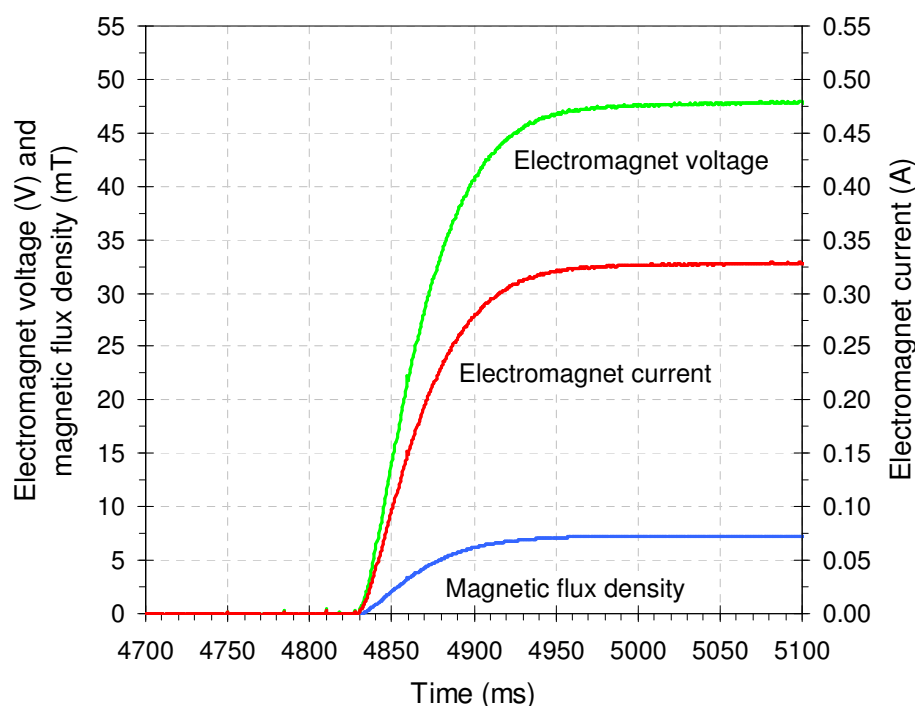


Figure 6.19: Relationship between electromagnet voltage rise and electromagnet coil current rise and magnetic flux density raise created (IPD = 40 mm with welding sample)

A support was built to hold the electromagnet parts in place (perpendicular to the torch and to the welding direction and adjacent to the arc region). This support was built in aluminium (paramagnetic) to minimise any influence on the magnetic field produced by the electromagnet, allows variation of the IPD (inter-pole distance) value and can be attached to manual or automatic GTAW and GMAW torches. The welding sample (Figure 6.13) was then tightly held (2 mm below the electromagnet) 10 mm above a moving welding table whilst the torch and electromagnet stayed steadily in place. During the tests, the sudden magnetic field was launched when the arc was around the mean point of the welding sample (enough time for arc stabilisation). A welding travel speed value (41 cm/min) was selected considering the more severe welding conditions (risk of burn-through at high currents). The electrode class (EWTh-2), diameter (2.4 mm) and tip angle (30°) were accordingly selected (based on the arc polarity and current range used). Figure 6.20 shows the rig used for this GTAW arc

stiffness assessment. Figure 6.21 shows the welding power source used. An acquisition system (hardware and software) already available was used and its calibration was corrected according to Appendix 6.



Figure 6.20: Rig used for the GTAW arc stiffness assessment



Figure 6.21: Welding power source (IMC Inversal 300) used for the GTAW arc stiffness assessment

A 40 mm inter-pole distance was used throughout the tests, since it provided higher values of magnetic flux density compared to 50 mm (Figure 6.18). The effects of the welding current level, arc length, torch angle and high-frequency current pulsing on the arc resistance to extinction were evaluated with the arc being deflected (and so blown out) backwards, as illustrated by Figure 6.22. In terms of comparison, the welding current level effects were also evaluated with the arc being deflected (and so blown out) forwards (Figure 6.23). For each of the GTAW variables assessed, the voltage applied on the electromagnet that produced the magnetic flux density capable of blowing out (or not) the arc was registered. Through this voltage and using the relationship showed in Figure 6.18, the correspondent magnetic flux density values that caused the arc extinction (or not) were found. It is worth repeating that the current flowing through the electromagnet coil (voltage applied to the electromagnet divided by the electromagnet electrical circuit resistance (145.9Ω)) is the responsible for generating the magnetic flux density. However, since the current values flowing through the electromagnet circuit are very low (Figure 6.19) and due to the direct relationship between voltage and current in this case, the electromagnet voltage input at the arc deflection and extinction was taken as a parameter to be compared throughout the tests as well.

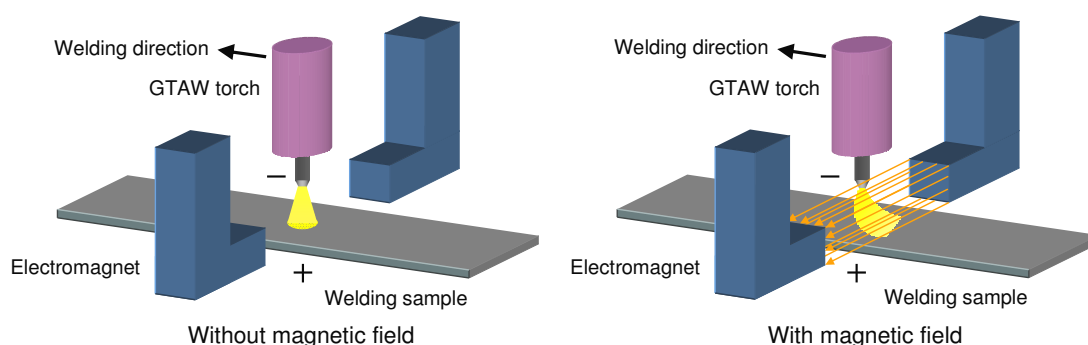


Figure 6.22: Arc deflected backwards by the electromagnet

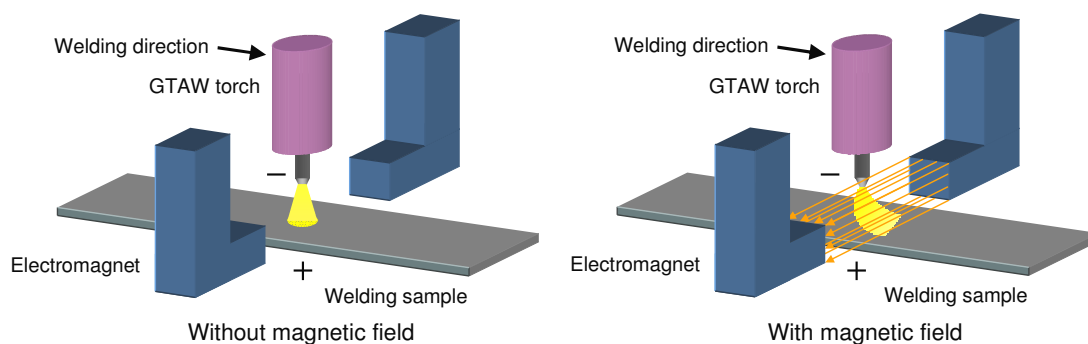


Figure 6.23: Arc deflected forwards by the electromagnet

Figure 6.24 shows an example of GTAW arc extinction due to an external magnetic field produced by the electromagnet; in this case the voltage applied on the electromagnet overcame (or at least matched) the level needed to produce the magnetic flux density value that blows out such an arc. During the extinction progression the arc voltage rises and becomes the open circuit voltage (provided by the power source) and the welding current falls to zero. If the voltage applied on the electromagnet does not overcome (or reaches) the value needed to promote the extinction, the arc is deflected only; in this case the arc increases its length and, thus, its voltage level, whilst the welding current remains the same (Figure 6.25).

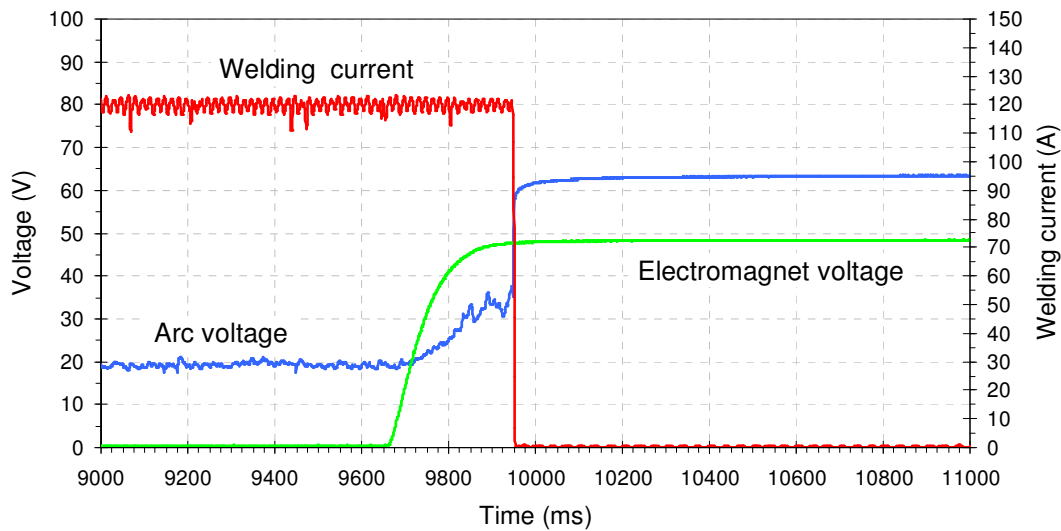


Figure 6.24: Example of GTAW arc extinction due to an external magnetic field

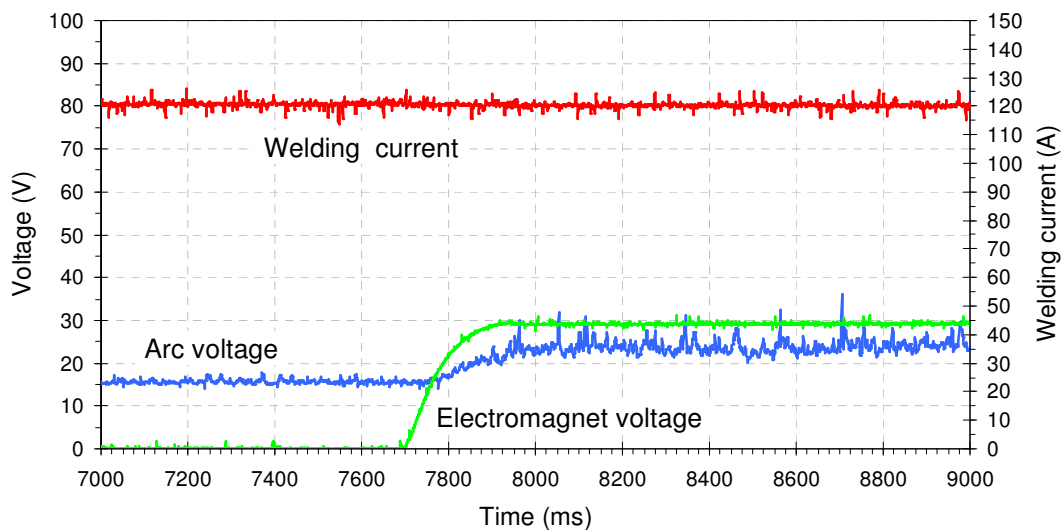


Figure 6.25: Example of GTAW arc deflection due to an external magnetic field

Eventually, high-speed filming of the GTAW arcs being deflected and blown out under certain conditions was carried out as an additional tool to evaluate the effects of the welding parameters on the arc resistance to extinction. In order to visualise the arc being deflected (and so being blown out), the high-speed camera was placed diagonally to the arc region as showed in Figure 6.26 and no extra illumination (back or front light) was employed.

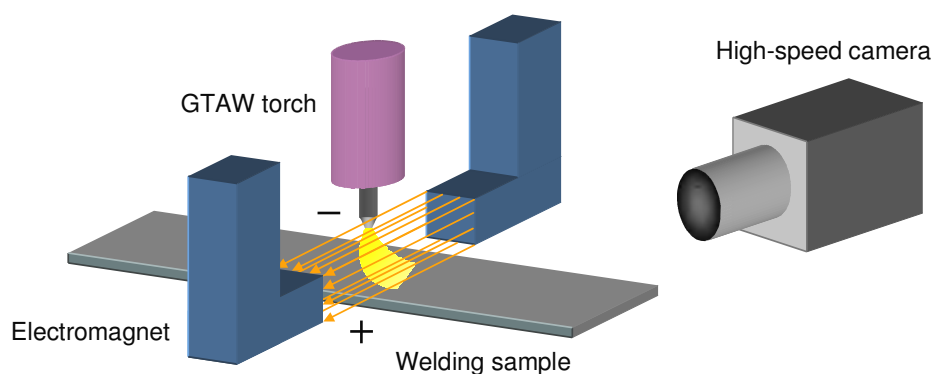


Figure 6.26: High-speed camera placed diagonally in relation to the arc being deflected

6.3.1 Welding current influence (arc deflected backwards)

The first variable to be put in trial was the current flowing through the arc. The current was varied for a constant arc length (10 mm), and for each selected value, the magnetic flux density capable of blowing out the arc was found through the voltage applied by the electromagnet voltage source. The arc length used was longer than the usual to ensure that the magnetic flux density range provided by the electromagnet would be able to blow out the arc in a variety of welding parameters setting. For each current value, the voltage applied on the electromagnet was varied at 1 V steps in order to find the edge where the GTAW arc starts to be blown out by the magnetic flux density produced. For each electromagnet voltage value, the sudden magnetic field was released and the arc extinction observed or not. If the extinction took place, the electromagnet voltage was kept at the same level and the test repeated to verify the repeatability of the result. If the extinction was confirmed, the voltage was increased in 1 V again and another test carried out to confirm that the region of arc extinction had been reached. The voltage value 1 V below this last level was taken as the GTAW arc resistance to extinction. Table 6.1 shows the current values evaluated and the respective magnetic flux densities needed to cause the GTAW arc extinction. Figure 6.27 shows how the arc resistance to extinction varies as the current flowing through the arc is increased.

Table 6.1: Welding current values evaluated and respective magnetic flux densities needed to cause the GTAW arc extinction (arc deflected backwards) (arc length = 10 mm; shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip)

Set current (A)	Mean actual welding current (A)	Coil Voltage (V)	Magnetic flux density at the arc extinction edge (mT)
30	33.8	14	2.37
40	42.5	15	2.54
50	50.7	17	2.87
60	59.3	19	3.21
70	68.5	21	3.55
80	77.3	24	4.06
90	85.6	27	4.57
100	94.9	30	5.08
110	104.6	32	5.42
120	112.2	34	5.75
130	121.0	38	6.43

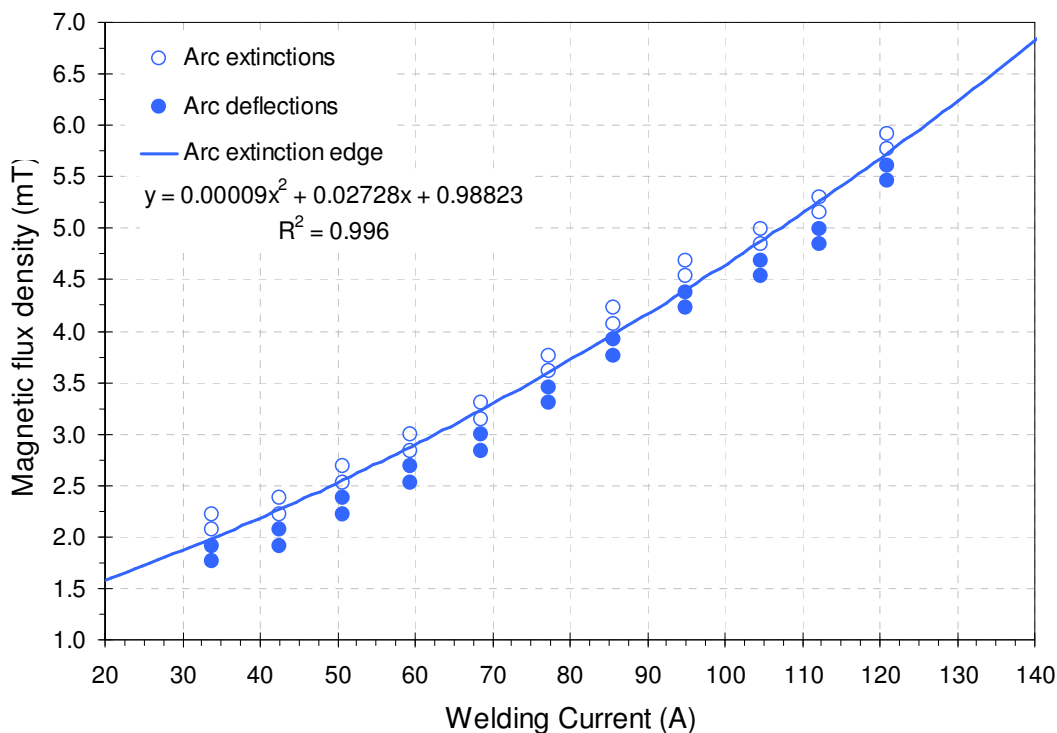


Figure 6.27: Relationship between welding current and resistance to extinction offered by the GTAW arc when it is deflected backwards (arc length = 10 mm; shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip)

The arc extinction edge curve (arc resistance to extinction) has a slightly parabolic tendency for the current range tested. The higher the electrical current flowing through the

arc, the more the arc resists to the extinction. This result is in accordance to Figure 2.23, in which Ueyama et al. (2006) showed the fall in the number of arc interruption occurrences in the trailing wire in tandem pulsed GMAW when the base current is raised. Considering the fact that the welding current is responsible for the formation of plasma jet (LANCASTER, 1986), by rising the current would give more stiffness to the arc¹. However, this is not so straightforward. As the current rise gives more stiffness to the arc by means of the plasma jet effect, it also increases the magnetic force acting on the arc. As the magnetic force (Eq. (6.5)) acts on each charged particle, the arc is deflected as soon as it leaves the electrode. The intensity of the resultant deflection is a balance. From one side, the magnetic force tries to deflect the charged particles. From the other side, the plasma jet tries to keep the particles in their original path. In other words, the arc self-induced magnetic field generates the plasma jet and the external magnetic field (from another arc or not or even resulted from an unbalanced magnetic field like those in arc blow) deflects the arc.

Thus, the stiffness promoted by the plasma jet should be totally valid only for situations without external (or unbalanced self-induced) magnetic fields. As it is discussed in Appendix 1, if a welding arc is deflected by a magnetic field, it changes its path and so its plasma jet direction. In addition, since the magnetic field force is directly related to the charged particles velocity, in other words, to the welding current, the gain in plasma jet intensity by raising the current would be contradicted by the raise in the magnetic force and consequent arc deflection. High arc deflections would lead to more risk of extinction. Thus, the effect of the welding current on the arc resistance to extinction might be related to effects beyond the plasma jet. Because of the parabolic tendency observed, these effects might be still non linear, as the plasma jet is.

Figure 6.28 shows how a GTAW arc set at 50 A is blown out. In order to make any effect more evident, the sudden magnetic field was released, in this case, by setting the electromagnet voltage at 19 V (2 V over the value that corresponded to the arc extinction edge for such a current level and further welding conditions). As the magnetic flux density produced by the electromagnet is raised (represented by the electromagnet voltage), the arc is deflected. At some points there are some spikes in the arc voltage signal, in which the arc seems to be in the imminence of being blown out. For some reason it recovers and resists the extinction as the electromagnet voltage continues to rise. At a certain point the arc is so deflected that it cannot resist any longer and the welding electrical circuit is broken, that is, the arc is extinguished (totally deionised). Consequently, the arc voltage rises to the open

¹ Further discussion regarding the plasma jet influence in welding arcs can be found at the end of this thesis in Appendix 1 (Models to Describe Plasma Jet, Arc Trajectory and Arc Blow Formation in Arc Welding).

circuit voltage value whilst the welding current drops to zero. Curiously, the regions close to the electrode and plate give the impression to be the last ones to be deionised (detail in Figure 6.29) and the arc seems to be “broken” somewhere in the arc column. As a comparison basis, Figure 6.30 shows another GTAW arc with the same welding conditions. Now the electromagnet voltage was set at 15 V (2 V below the value that corresponded to the arc extinction edge for such a current level and further welding conditions). As the magnetic flux density (electromagnet voltage) raised, the arc was deflected, which slightly increased its voltage value. No imminence of extinction was observed in such a case.

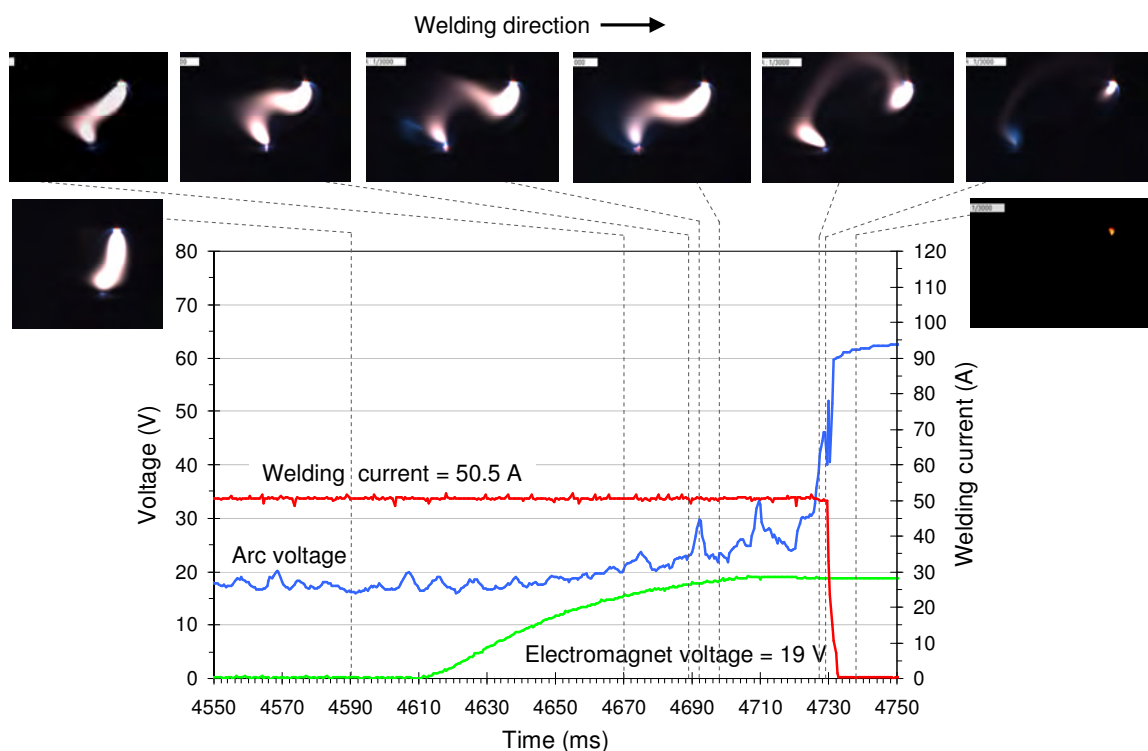


Figure 6.28: A 50 A GTAW arc extinction when it is deflected backwards (arc length = 10 mm; shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip) (data and image acquisition synchronised at 2000 Hz)

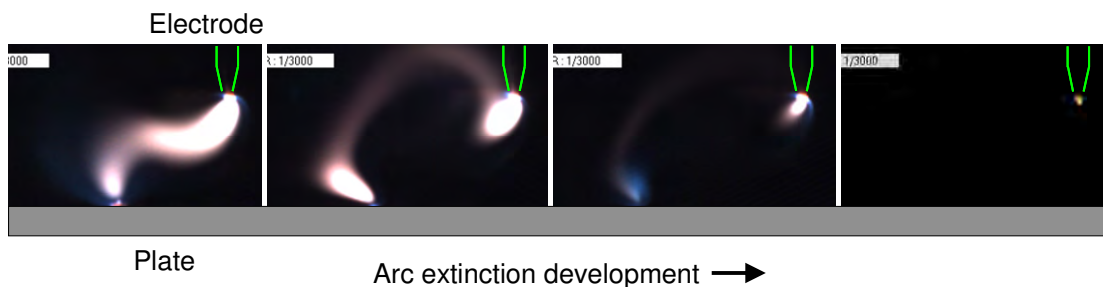


Figure 6.29: Regions close to the electrode and plate being the last ones to lose the glow during the arc extinction

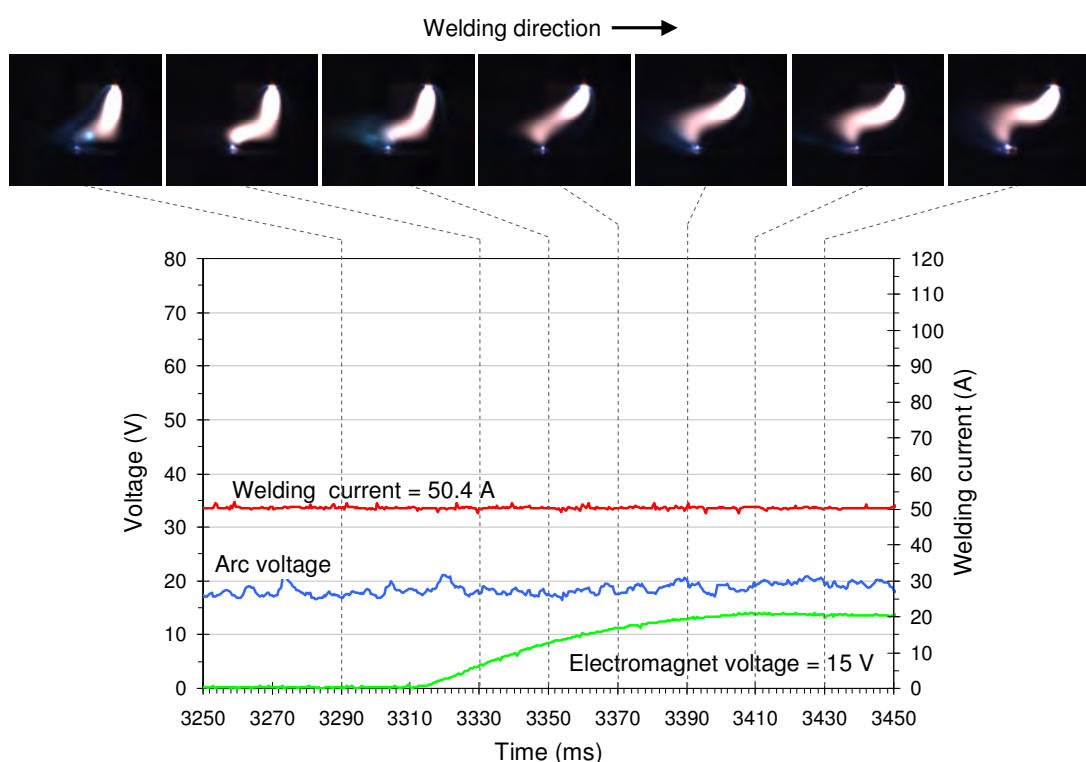


Figure 6.30: A 50 A GTAW arc deflected backwards (arc length = 10 mm; shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip) (data and image acquisition synchronised at 2000 Hz)

As shown by Figure 6.31, at higher current levels (95 A in this case), the arc was blown out in the same way as presented in Figure 6.28. However, it demanded a more extensive deflection, which, in turn, meant that a more intense rise in the magnetic flux density (electromagnet voltage) had to be applied. In this case, the electromagnet voltage was set at 32 V (2 V over the value that corresponded to the arc extinction edge for such a current level and further welding conditions). Just before being blown out, the arc presented some extinction imminences (voltage spikes) as it was noticed for the welding current at 50 A (Figure 6.28). As it is exemplified in Figure 6.32, these spikes in the voltage signal appear in a larger number at the arc extinction edge (electromagnet voltage at 30 V). As a means of comparison, Figure 6.33 shows another GTAW arc set at 95 A with the same welding conditions. This time the electromagnet voltage was set at 28 V (2 V below the value that corresponded to the arc extinction edge for such a current level and further welding conditions). As the magnetic flux density (electromagnet voltage) increased, the arc was significantly deflected (compared to Figure 6.30), which considerably raised its voltage value. Even so, no imminence of extinction was observed in such a case.

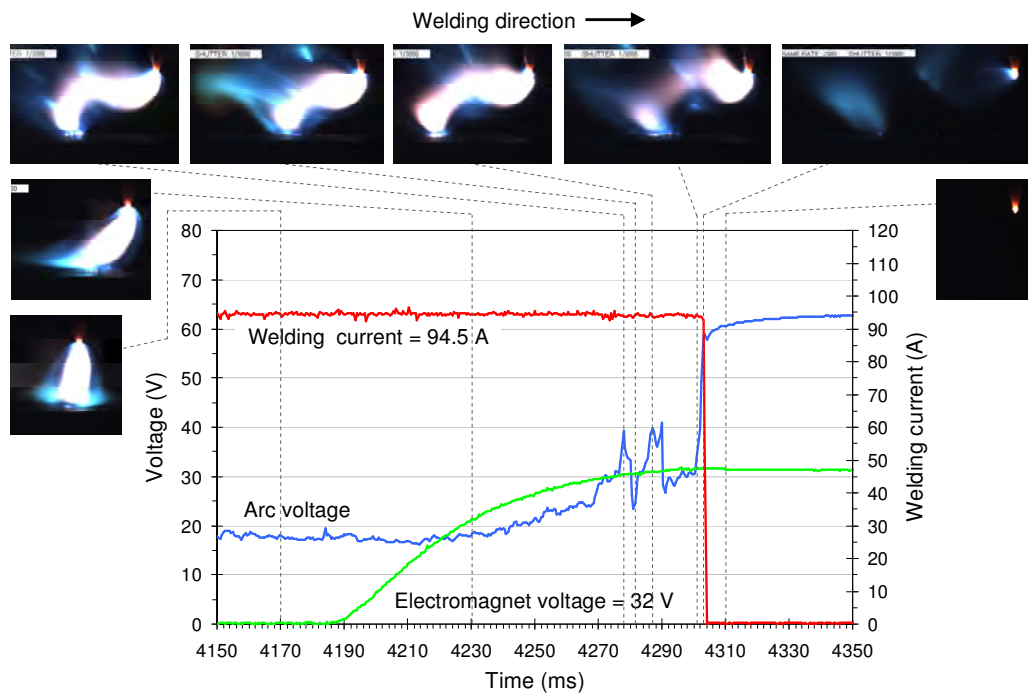


Figure 6.31: A 95 A GTAW arc extinction when it is deflected backwards (arc length = 10 mm; shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip) (data and image acquisition synchronised at 2000 Hz)

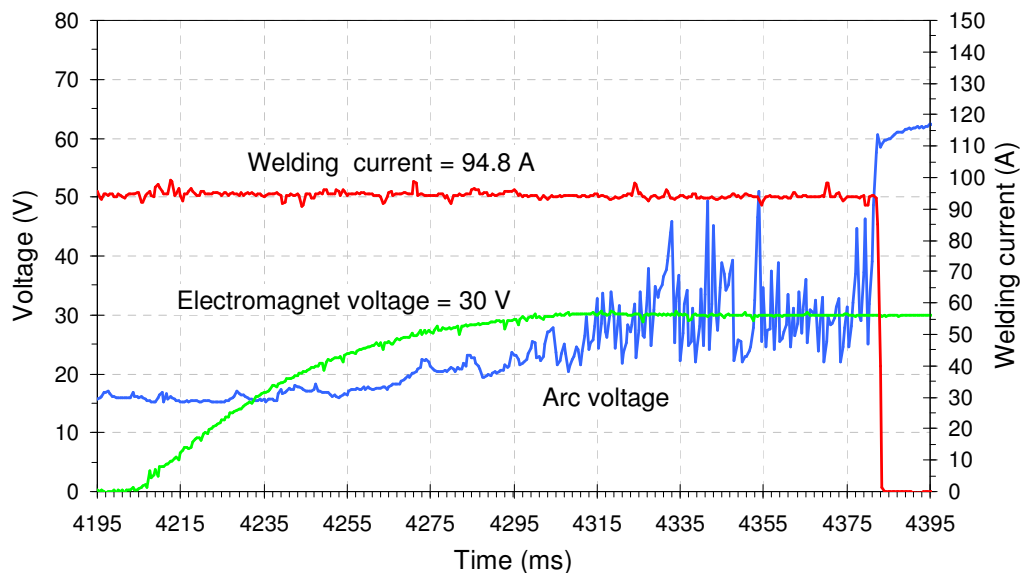


Figure 6.32: Various spikes in the voltage signal of a 95 A GTAW arc as it is deflected backwards and so blown out by a magnetic field right at the arc extinction edge (arc length = 10 mm; shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip) (data and image acquisition synchronised at 2000 Hz)

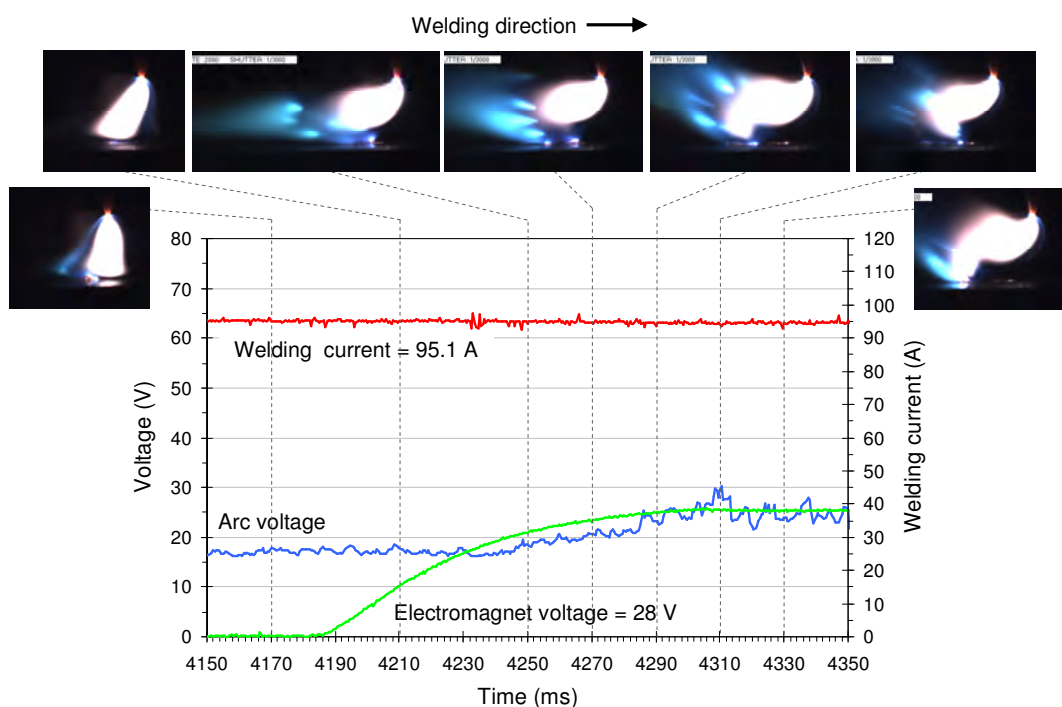


Figure 6.33: A 95 A GTAW arc deflected backwards (arc length = 10 mm; shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip) (data and image acquisition synchronised at 2000 Hz)

As the arc is formed by charged particles (electrons and ions), if the arc is subjected to an external, perpendicular and uniform magnetic field, its charged particles experience a typical motion. In this case, the magnetic force is always perpendicular to both the velocity of the particle and the magnetic field that created it. For this reason, charged particles move in a circle around magnetic field lines; this is called cyclotron motion. The following photographs (Figure 6.34) were made by Stenzel (2000). They demonstrate how single charged particles moves in magnetic fields. A weak electron beam was injected from an oxide-coated cathode into a low pressure argon gas partially ionising it. The trajectory of the beam of electrons is visible due to light excitation when the beam collides with argon atoms. Figure 6.34 (a) shows a 100 eV electron beam injected into the neutral gas without applying the external magnetic field. According to Stenzel (2000), the beam scatters by collisions and beam-plasma instabilities. Figure 6.34 (b) shows another 100 eV electron beam, but now injected perpendicular to a DC magnetic field (pointing into the plane). It is worth noting that the beam light weakens with propagation distance. Finally, Figure 6.34 (c) shows a lower energy beam injected across a magnetic field as in image (b). The cyclotron radius is decreased, which indicates that low energy plasmas (low current arcs) are more deflected than high energy ones.

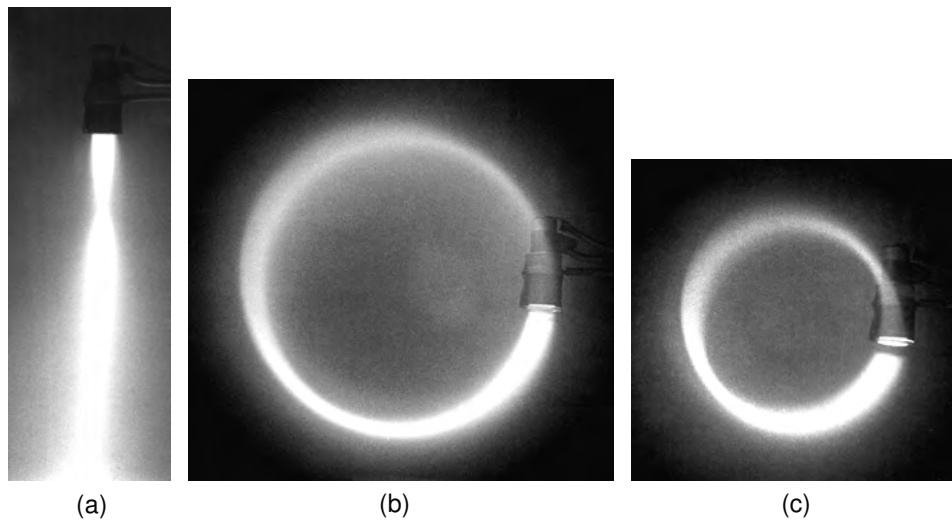


Figure 6.34: (a) A 100 eV electron beam injected into a neutral gas without applying external magnetic field; (b) A 100 eV electron beam injected perpendicular to a DC magnetic field; (c) A lower energy electron beam injected across a magnetic field as in (b) (STENZEL, 2000)

The cyclotron motion tendency is put in evidence by the shape the arc has as it leaves the electrode tip (region 1 in Figure 6.35) when it is deflected. However, at certain point along its extension, the arc has to change its direction as it needs to reach the plate in order to keep the welding circuit closed and remains “alive”. Thus, such a change in orientation during the arc defection results in two well defined regions; one under the effect of the cyclotron motion (region 1) and another created in consequence of the welding circuit (region 2). The distinction between those regions gets more evident as the arc defection progresses. Taking into account the formation of both regions, Figure 6.36 illustrates what happens as the arc is deflected by an external magnetic field.

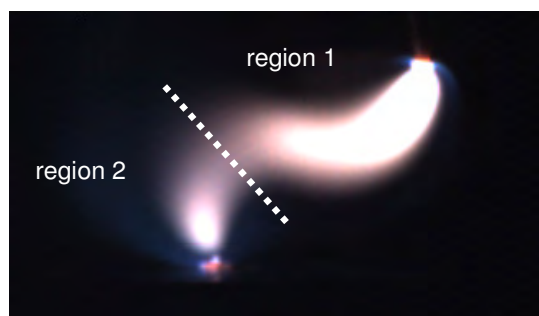


Figure 6.35: Characteristic shape assumed by the arc when it is largely deflected

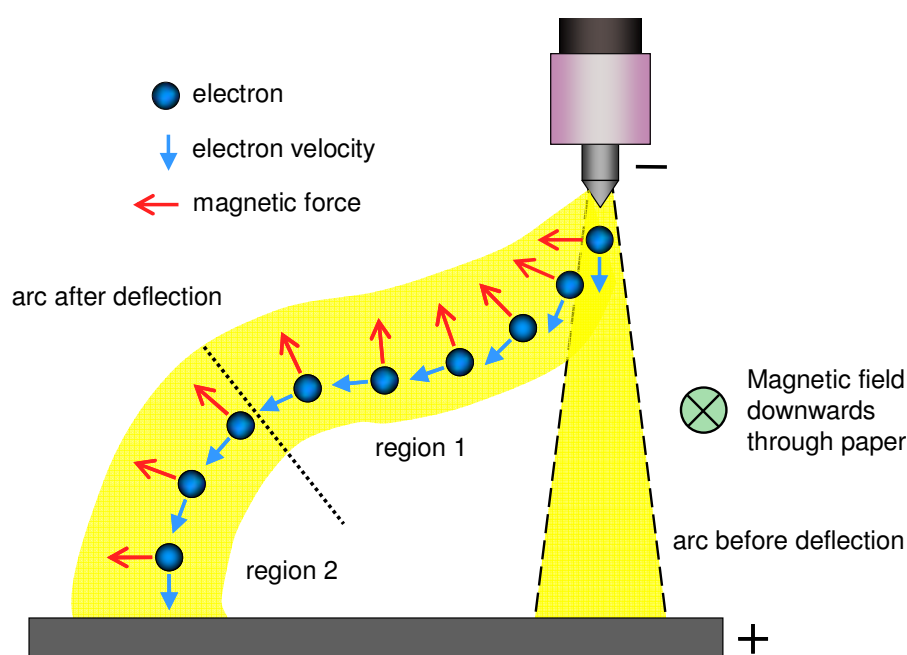


Figure 6.36: Illustration on how the arc would get its “deflected shape” in consequence of an intense and external magnetic field

In order to take a closer look at the arc extinction, Figure 6.37 shows the event in a more detailed way (50 ms interval). In this case, a 50 A arc was subjected to a magnetic field well beyond (10 V over) the needed at the arc extinction edge for such a current level and further welding conditions. Even with the much more intense magnetic field, the small spikes were verified in the voltage signal just before the extinction. In this case (50 A arc subjected to 27 V electromagnet voltage), the extinction took place when the arc reached approximately 54 V. By amplifying the extinction moment when a 50 A arc was blown out by a 19 V electromagnet voltage (Figure 6.28), the arc was verified to disappear at around 52 V. These values indicate that the arc voltage at the extinction moment might be independent from the electromagnet voltage applied, that is, from the magnetic flux density. In order to verify such possibility, Figure 6.38 shows arc voltage values at the moment 120 A arcs are blown out by magnetic fields starting from the arc extinction edge value. For this level of welding current, the arc voltage at the extinction moment was randomised, not showing any straightforward relationship to the magnetic flux density (electromagnet voltage) applied. As the way the arc is blown out was verified to be independent from the welding current level used, this randomised behaviour regarding the arc voltage at extinction should be applicable to low-current arcs as well. Despite this verification, a question could emerge also concerning the possible effect the welding current would have on the arc voltage at the extinction moment. Taking this issue into account, Figure 6.39 shows the arc voltage value at the moment the arc is blown out for various welding current values. In this case, the arc voltage

values were found mainly for the electromagnet set at voltages correspondent to the arc extinction edge. Again, a randomised effect was verified, which indicates that there is no influence of the welding current on the arc voltage value the arcs are blown out. However, there seems to be a voltage range in which the arc extinction takes place (37 to 57 V). It is worth saying that the exact moment the arc is blown out is very hard to be determined since all the images presented here deal with the visible light emitted by the arc, which depends on optical filters used, camera shutter selected, etc. However, as a mean of reference and to facilitate the analysis, throughout this work the arc extinction moment is considered as the point the welding current starts to fall.

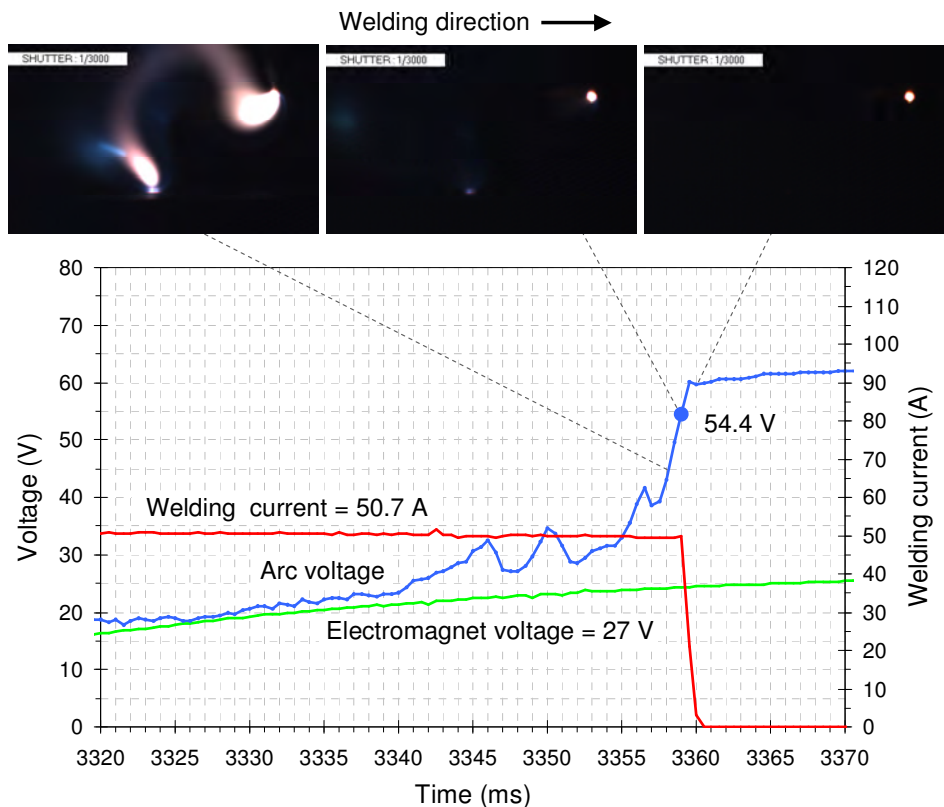


Figure 6.37: A 50 A GTAW arc extinction when it is deflected backwards by a magnetic field well beyond the defined in the arc extinction edge (arc length = 10 mm; shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip) (data and image acquisition synchronised at 2000 Hz)

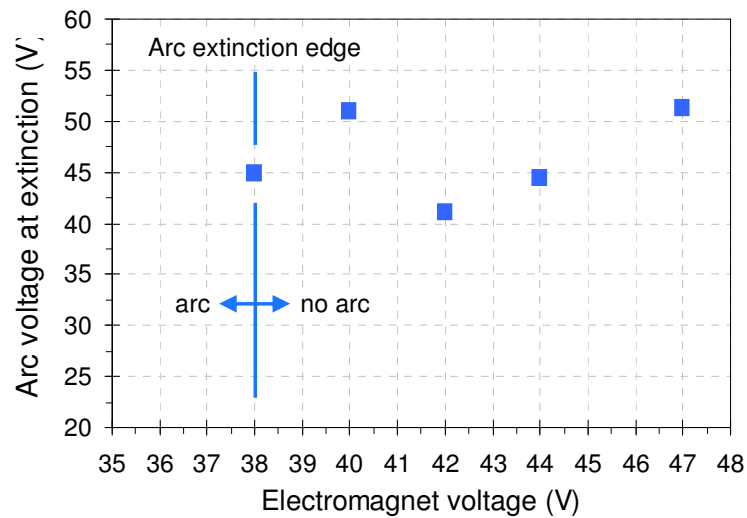


Figure 6.38: Arc voltage values at the moment 120 A arcs are deflected backwards and so blown out by magnetic fields starting from the arc extinction edge

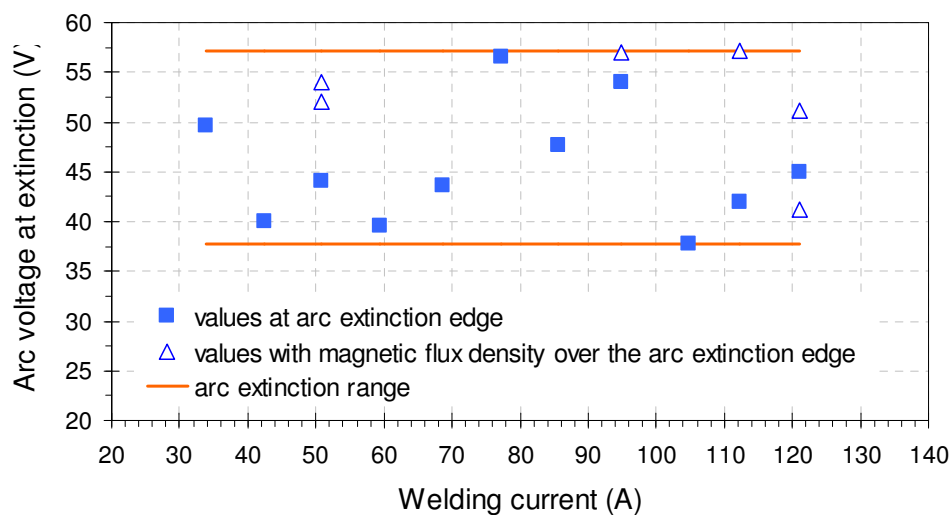


Figure 6.39: Arc voltage value at the moment the arc is blown out for various welding current values

6.3.2 Arc length influence (arc deflected backwards)

The second variable to be assessed was the arc length. The welding current was regulated at 50 A (existence of problems in tandem pulsed GMAW and the lack of stiffness is more evident with low currents) and at a higher level and the arc length increased (15 mm) and decreased (5 mm) (Figure 6.40). For each extra arc length, the arc extinction edge (arc resistance to extinction) was found. In another words, the magnetic flux density value that firstly blew out the arc with repeatability was determined. Table 6.2 shows the arc length

values evaluated and the respective magnetic flux densities needed to cause the GTAW arc extinction. Figure 6.41 shows the arc length influence on the arc resistance to extinction.

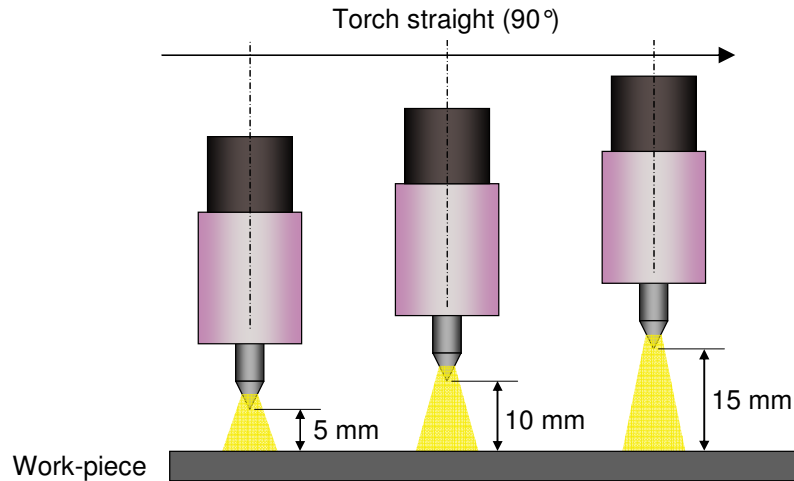


Figure 6.40: Arc lengths evaluated regarding the arc resistance to extinction

Table 6.2: Arc length values evaluated and respective magnetic flux densities needed to cause the GTAW arc extinction (arc deflected backwards) (shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip)

Arc length (mm)	Set weld. current (A)	Mean actual weld. current (A)	Coil Voltage (V)	Magnetic flux density at the arc extinction edge (mT)
5	50	50.1	35	5.30
15	50	50.8	8	1.14
5	100	95.4	48	no extinction*
15	100	93.8	15	2.22
5	80	76.9	47	7.15

* A 48 V coil voltage (maximum value available) was not able to blow out a "100 A" and 5 mm arc.

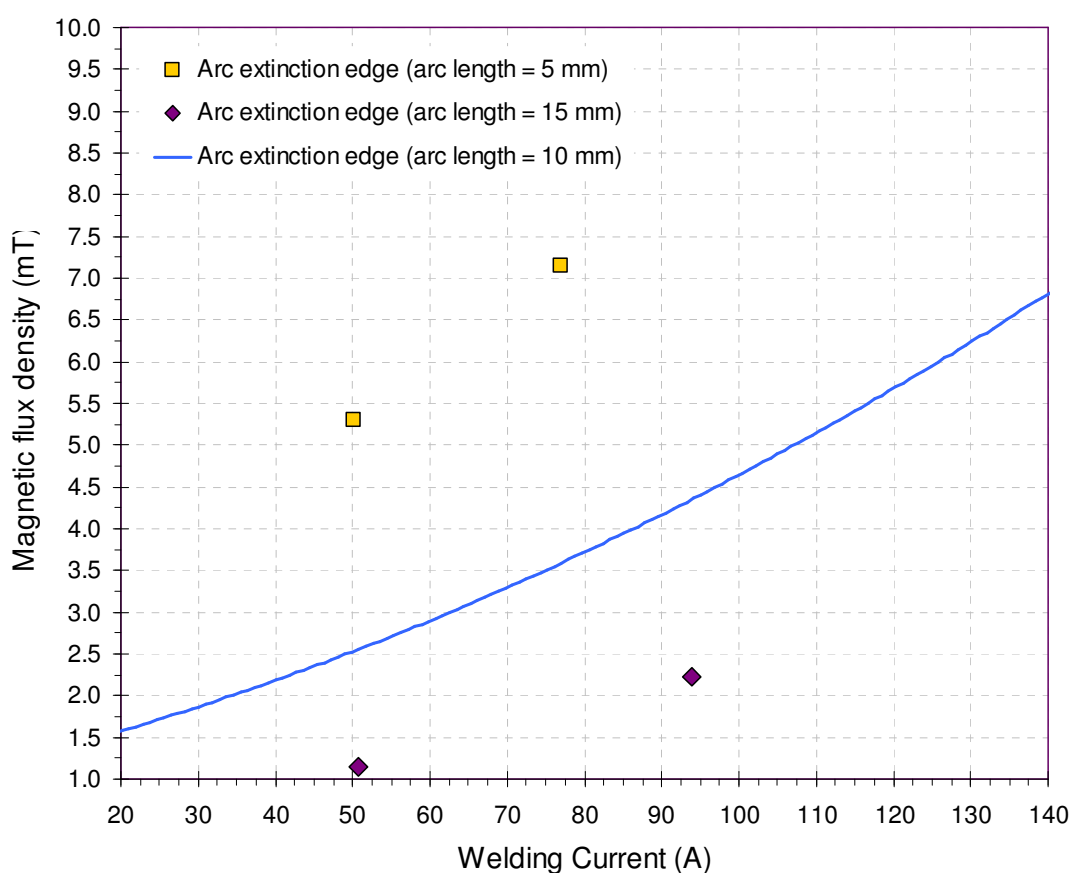


Figure 6.41: Influence of the GTAW arc length on the arc extinction edge curve when the arc is deflected backwards (welding current = 50 A; shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip)

Arc length variation displaces the extinction edge curve. If the arc length is shortened, the arc resistance to extinction is increased. On the other hand, if the arc length is increased, it makes the arc extinction easier. This result comes in accordance to the tendency expressed by Eq. (6.5), in which the longer the length of the electrical current conductor (arc), the bigger the consequential force due to an external magnetic field. Thus, as the arc deflection is due to the magnetic force created and the responsible for blowing out the arc, the longer the arc length, the higher the risk of extinction.

Figure 6.42 shows, for a given welding current, the influence of the arc length on the resistance to extinction offered by the GTAW arc in a different way (magnetic flux density at arc extinction versus arc length). It is possible to observe that the arc extinction edge curve seems to have a parabolic tendency. The gain in arc resistance to extinction is more pronounced when the arc length is varied from 10 to 5 mm than when from 15 to 10 mm. This indicates that non linear factors (arc superficial area, for instance) might be playing roles on the arc resistance to extinction when the arc length is varied.

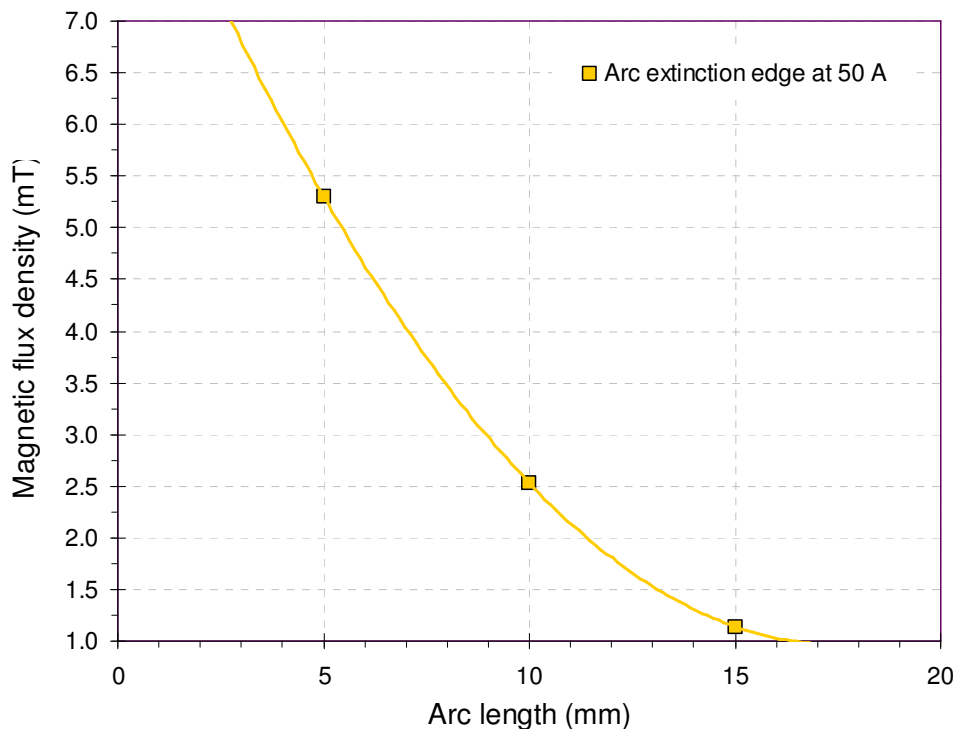


Figure 6.42: Influence of arc length on the resistance to extinction offered by the GTAW arc when it is deflected backwards (welding current = 50 A; shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip)

Figure 6.43 shows how a GTAW arc set at 50 A is blown out when it has a 5 mm length. In order to make any effect more evident, the sudden magnetic field was released, in this case, by setting the electromagnet voltage at 37 V (2 V over the value that corresponded to the arc extinction edge for such a current level, arc length and further welding conditions). The extinction pattern is similar to the one described previously (Figure 6.28), except for the longer time (around 310 ms) needed to reach the extinction (from the magnetic field rise to the extinction moment). This fact indicates that short arcs have the resistance to extinction significantly increased (even with the electromagnet voltage set at 2 V above the arc extinction edge, the arc demanded a long time to be extinguished). In order to validate such an indication, Figure 6.44 shows how a 50 A and 15 mm arc is blown out. Once more the electromagnet voltage was set at 2 V over the value that corresponded to the arc extinction edge for such a current level, arc length and further welding conditions (10 V). The arc extinction (physical development and time) was like the one described previously (Figure 6.28). This fact reinforces the way the arc resistance to extinction varies as the arc length is increased; the shorter the arc length, the more pronounced the gain in resistance to extinction. Figure 6.45 compares the extinction of 50 A GTAW arcs as their lengths are increased.

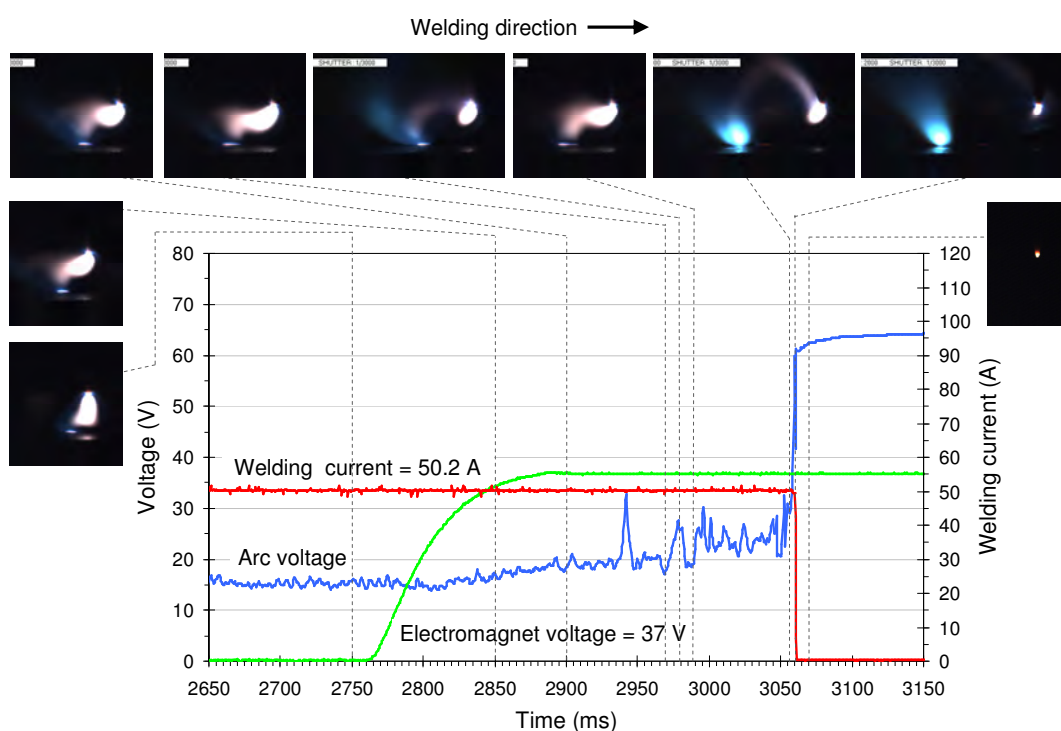


Figure 6.43: A 5 mm long GTAW arc extinction when it is deflected backwards (welding current = 50.2 A, shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip) (data and image acquisition synchronised at 2000 Hz)

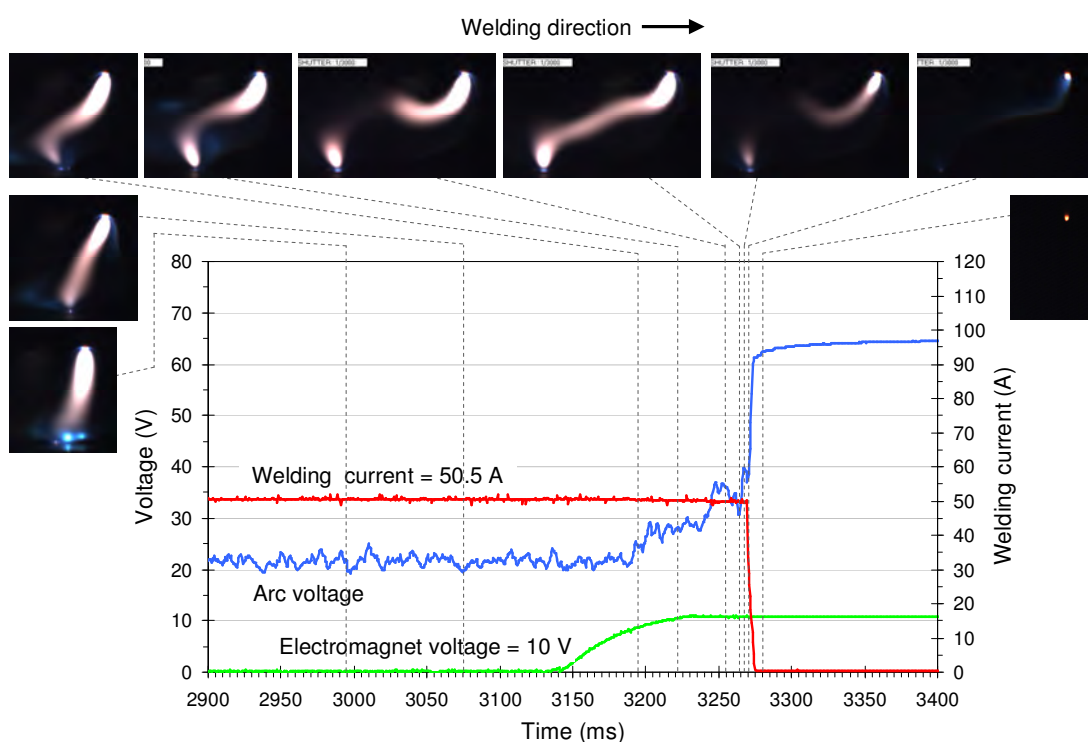


Figure 6.44: A 15 mm long GTAW arc extinction when it is deflected backwards (welding current = 50.5 A, shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip) (data and image acquisition synchronised at 2000 Hz)

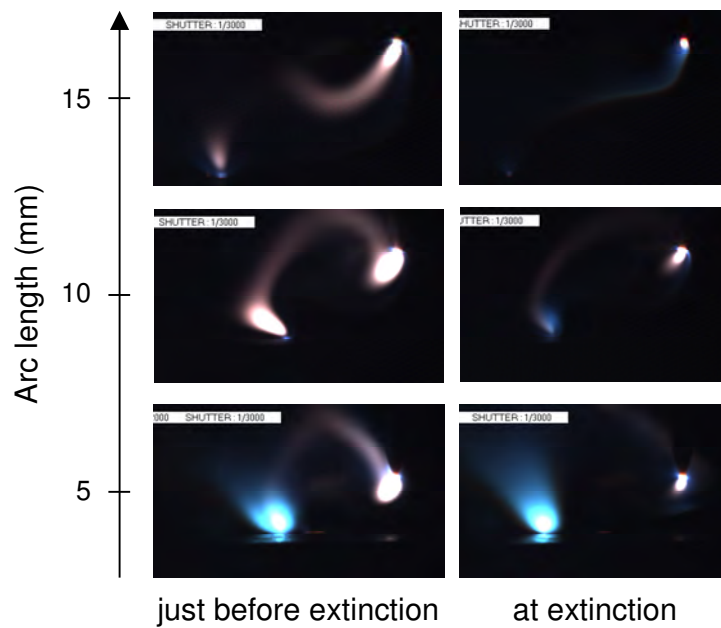


Figure 6.45: Arc length influence on the extinction of 50 A GTAW arcs (shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip)

Figure 6.46 shows arc voltage values at the moment the arc is blown out for different arc lengths. This factor does not seem to have any defined effect on the arc voltage the arcs are blown out. The values were randomised and tended to fit in the arc voltage range defined in Figure 6.39.

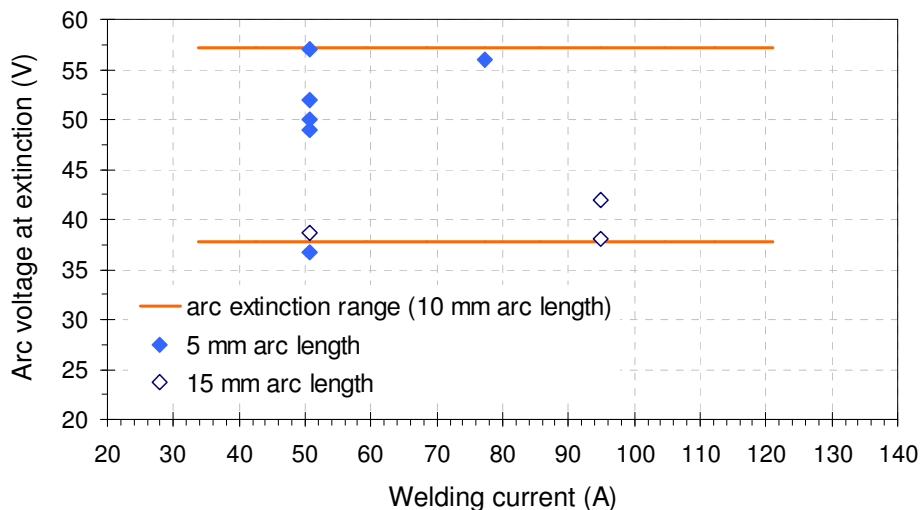


Figure 6.46: Arc voltage values at the moment the arc is blown out for different arc lengths

6.3.3 Torch angle influence (arc deflected backwards)

The torch angle influence was also evaluated for two welding current levels. Figure 6.47 shows the torch angles used. Table 6.3 shows the current values evaluated and the respective magnetic flux densities needed to cause the GTAW arc extinction. Figure 6.48 shows how the arc resistance to extinction changes as the torch is utilised pushing and trailing the weld bead.

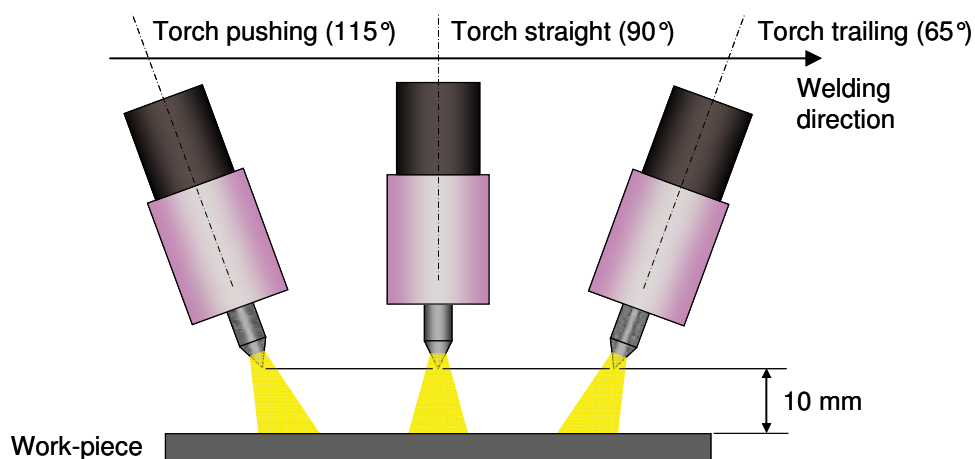


Figure 6.47: Torch angles evaluated regarding the arc resistance to extinction

Table 6.3: Torch angles evaluated and respective magnetic flux densities needed to cause the GTAW arc extinction (arc deflected backwards) (arc length = 10 mm; shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip)

Torch angle (°)	Set weld. current (A)	Mean actual weld. current (A)	Coil Voltage (V)	Magnetic flux density at the arc extinction edge (mT)
65	50	50.3	19	2.84
115	50	50.7	26	3.91
65	80	77.6	25	3.76
115	80	78.0	41	6.23

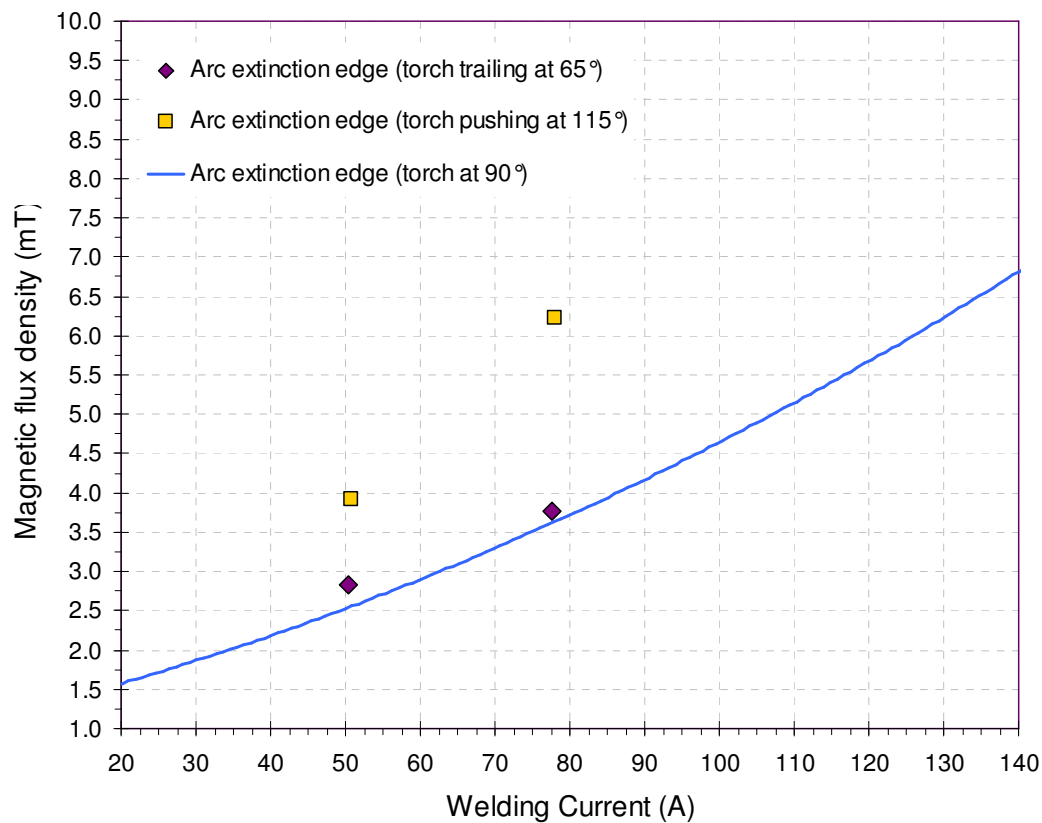


Figure 6.48: Influence of the GTAW torch angle on the arc extinction edge curve when the arc is deflected backwards (arc length = 10 mm, shielding gas = Ar at 14 l/min; electrode: EWTh-2, 2.4 mm, 30° tip)

At least for the angles tested, if the torch (arc) angle is set in order to “push” the weld pool (115°), it increases the arc resistance to extinction (displaces the extinction edge curve upwards). In contrast, if the torch (arc) angle is set in a way to “trail” the weld pool (65°), the arc resistance to extinction seems to remain almost the same. As it is illustrated by Figure 6.49, if the arc is set to “push” the weld pool, firstly it needs to be deflected to the vertical position and after that up to a point where it is blown out. This fact is also indicated by the slight fall in the arc voltage value as the magnetic voltage starts to rise. After that, as the electromagnet voltage continues to increase, the arc is being deflected backwards, the arc voltage starts to rise and the extinction takes place.

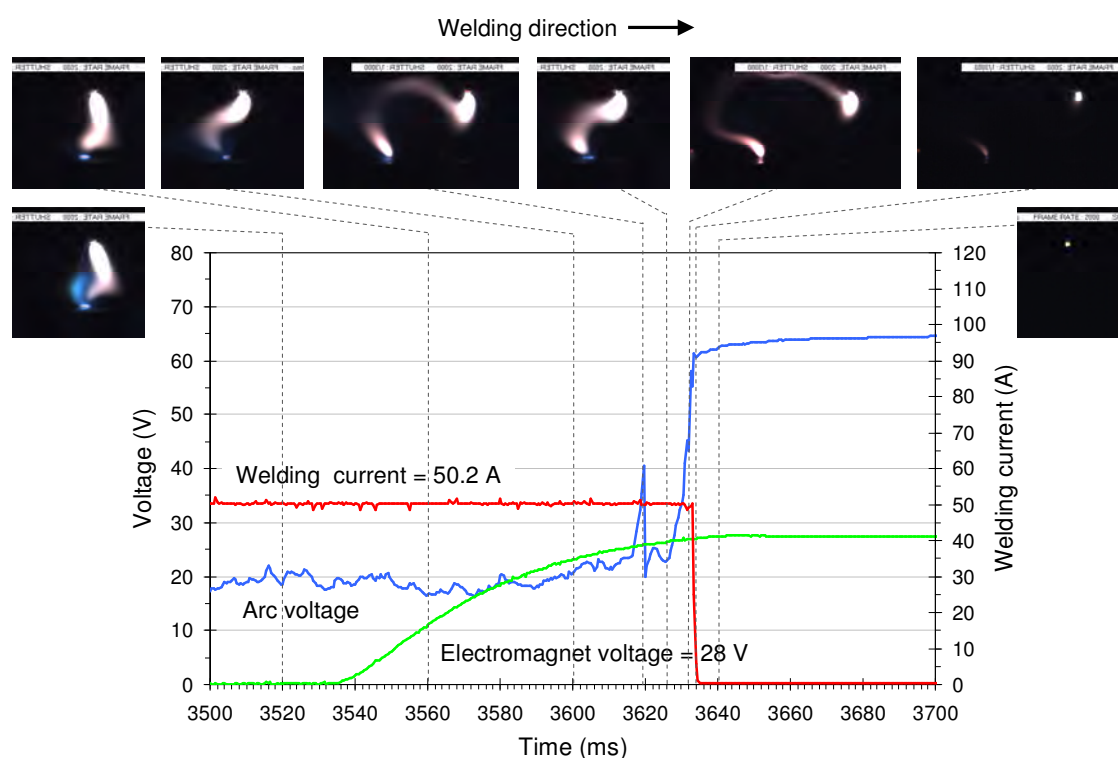


Figure 6.49: A 50 A GTAW arc extinction when it is set to “push” the weld pool (115°) and deflected backwards (arc length = 10 mm; shielding gas = Ar at 14 l/min; electrode: EWTh-2, 2.4 mm, 30° tip) (data and image acquisition synchronised at 2000 Hz)

Figure 6.50 shows how the arc is blown out if it is set to “trail” the weld pool. The arc showed a curious extinction pattern. The extinction followed the normal process except for the abnormal arc recovery at an intermediate current level. The arc was blown out, the current started to fall but, for some reason, the connection with the work-piece was re-established. However, it seems that before the current could rise to the welding level, the arc was definitely blown out. Now, in relation to the arc resistance to extinction, it was expected that trailing angles would lower the arc extinction edge curve, since the arc would be already “deflected” backwards. The fact the arc is blown out almost at the same level as when the torch was placed straight may be a consequence of the way the arc was positioned in the magnetic field; electrode tip centralized in relation to the electromagnet poles (part of the arc was under the influence of lower magnetic flux densities (Figure 6.15)). With that in mind, the electromagnet voltage level able to blow out the arc had to be increased to compensate any fall in the magnetic flux density. The same problem (part of the arc subjected to lower magnetic flux) may have occurred when the arc was “pushing” the weld pool as well. However, in that case, the effect of displacing the extinction edge curve upwards would be probably less intense, since the arc is driven to regions of more intense magnetic flux density anyway as it is deflected backwards.

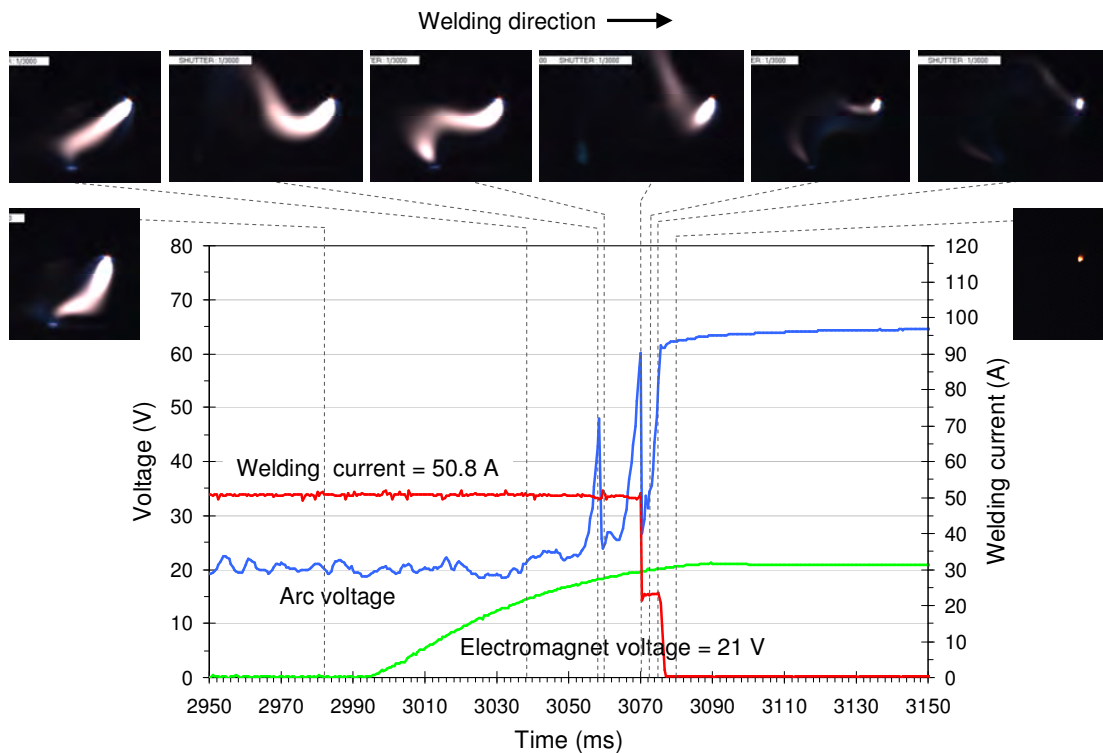


Figure 6.50: A 50 A GTAW arc extinction when it is set to “trail” the weld pool (65°) and deflected backwards (arc length = 10 mm; shielding gas = Ar at 14 l/min; electrode: EWTh-2, 2.4 mm, 30° tip) (data and image acquisition synchronised at 2000 Hz)

Figure 6.51 shows arc voltage values at the moment the arc is blown out for different torch angles. As it has been happening to all the welding factors evaluated so far, this factor does not seem to have any effect on the arc voltage the extinctions take place. The values were randomised and tended to fit in the arc voltage range defined in Figure 6.39.

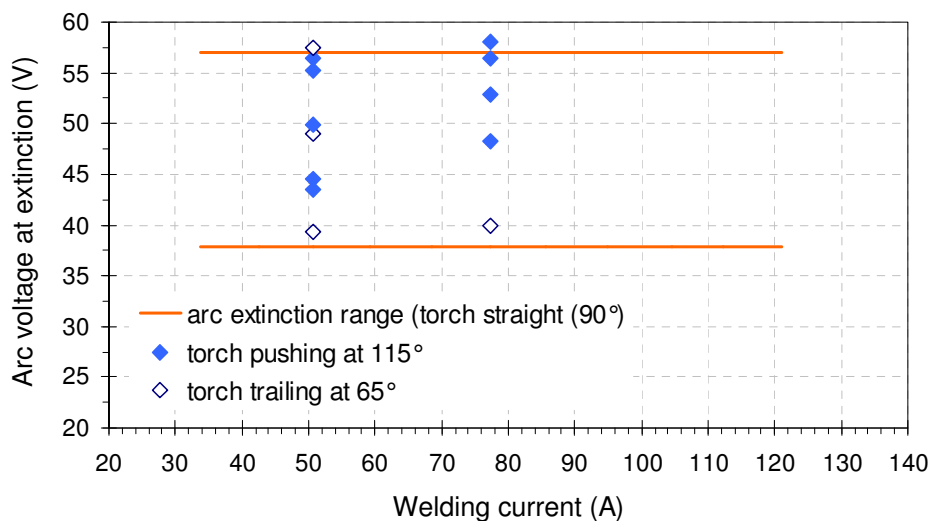


Figure 6.51: Arc voltage values at the moment the arc is blown out for different torch angles

6.3.4 High-frequency current pulsing influence (arc deflected backwards)

High-frequency current pulsing has been mentioned as able to improve the arc stiffness. GTAW dedicated power sources designed to operate with this approach, for example, can pulse the welding current in frequencies as high as 20 kHz (OTC, 2009). Cook and Eassa (1985) simulated the arc pressure on the weld pool as a measure of arc stiffness and stated that by using high-frequency current pulsing in GTAW it is possible to increase the arc pressure as much as ten times that of a DC arc with the same arc power input. They also showed that the pressure over the weld pool is mainly dependent on the effective current value of the pulsed current wave. Dzelnitzki (2000) shows the GTAW arc pressure as a function of the pulsing frequency (Figure 6.52). The gain in arc pressure is significant up to a frequency of about 5 kHz. However, despite being able to improve the arc pressure over the weld pool, nothing is mentioned regarding any relationship between high-frequency current and arc stiffness in the presence of external magnetic fields.

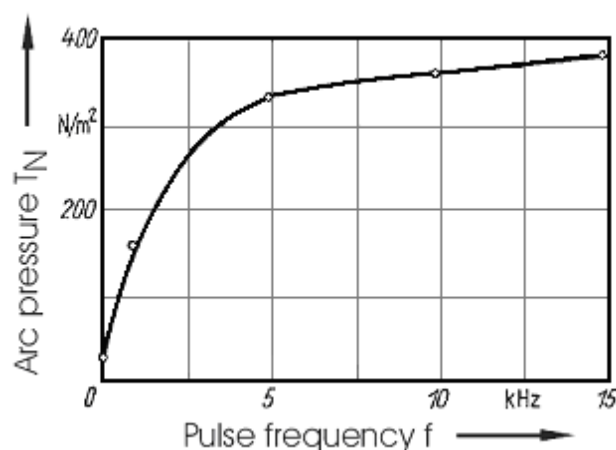


Figure 6.52: Arc pressure as a function of the pulse frequency (medium current: 50 A; pulse current: 150 A; base current: 5 A; arc length: 2 mm) (DZELNITZKI, 2000)

Considering this lack of information, high-frequency current pulsing was evaluated regarding the arc resistance to extinction. Table 6.4 shows the high-frequency current pulsing parameters used and the respective magnetic flux densities needed to cause the GTAW arc extinction in each case. Despite the tests were carried out in GTAW arcs, as a means of achieving a high-frequency pulsing, the power source was set to operated in direct polarity (electrode negative) GMAW (maximum frequency much higher than if the power source was set to GTAW mode). Figure 6.53 shows the effects of high-frequency current pulsing on the GTAW arc resistance to extinction.

Table 6.4: High-frequency current pulsing parameters and respective magnetic flux densities needed to cause the GTAW arc extinction (arc deflected backwards) (arc length = 10 mm; shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip)

Frequency (Hz)	I_p (A)	t_p (ms)	I_b (A)	t_b (ms)	Mean actual weld. current (A)	Coil Voltage (V)	Magnetic flux density at the arc extinction edge (mT)
500	70	1.0	30	1.0	49.8	15	2.22
500	120	1.0	80	1.0	95.8	30	4.53
1000	70	0.5	30	0.5	49.1	12	1.76
1000	120	0.5	80	0.5	96.2	25	3.76

I_p : peak current; t_p : peak current time; I_b : base current; t_b : base current time.

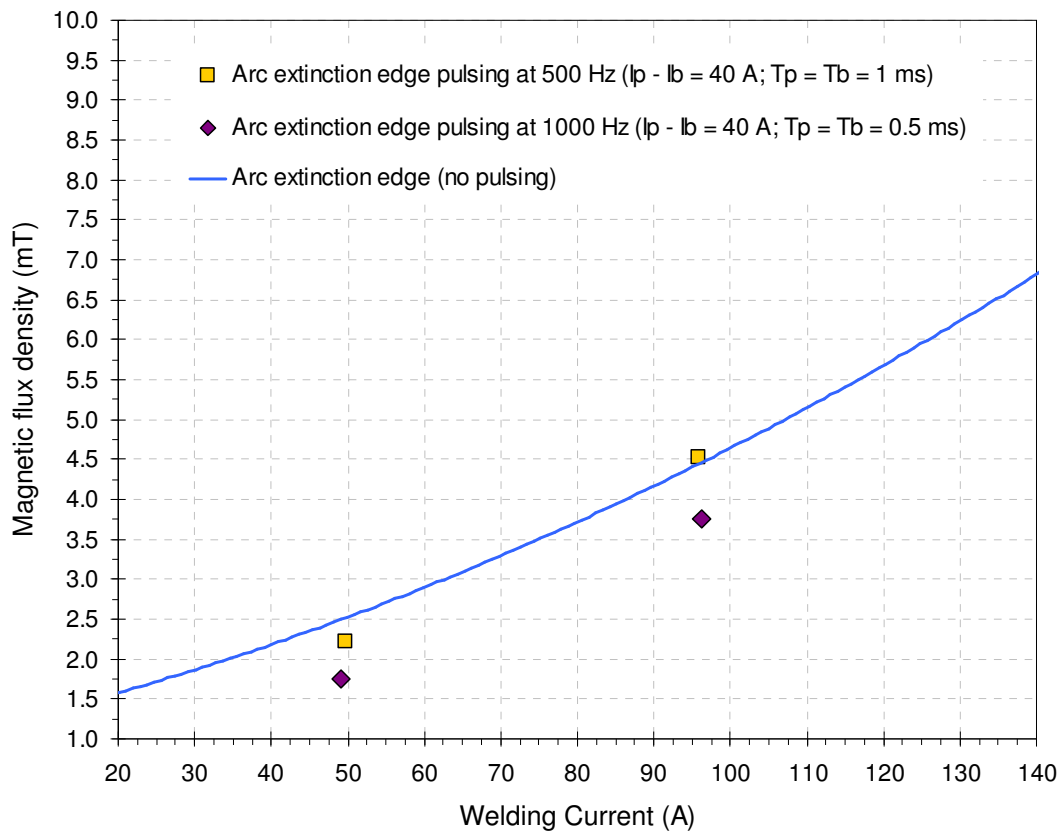


Figure 6.53: Influence of high-frequency current pulsing on the arc extinction edge curve when the arc is deflected backwards (arc length = 10 mm, shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip)

Curiously, at least for the conditions tested (two levels of mean current), the utilisation of high-frequency current pulsing in general tends to lower the arc extinction edge curve, and the higher the pulsing frequency, the worse the arc resistance to extinction. This fact comes in disagreement with the current literature and got more evident for the lowest level of current

tried (around 50 A). It seems that the negative effect becomes less intense and the arc extinction edge curve is less displaced as the mean welding current is raised. Further tests using higher mean current levels would be necessary to make any categorical conclusion regarding this indication.

A possible explanation for the decrease in the resistance to extinction due to the use of high-frequency current pulsing may be related to the fact the current falls to a low value (I_b) once a pulsing cycle. The arc was verified to be extinguished always when the welding current was in its base current time (t_b) (Figures 6.54 and 6.55). As the current flowing through the arc plays a decisive role on the extinction (the lower the current level, the lower the magnetic flux density required to cause the extinction (Figure 6.27)), it is reasonable to think the arc would be blown out during the base current time (low current level, that is, low resistance to extinction). From this point of view, each time the current falls to the base level the arc is more prone to extinction. Thus, the possibility of extinction may be related to the level of base current used, to the number of times the current goes to this level and/or time it remains at this level. Despite the current goes to the low level more times with the pulsing frequency set at 1000 Hz, for a given time, the current remains at this low level the same time as when the pulsing frequency is set at 500 Hz. Therefore, it is hard to make any definitive statement regarding the reasons for the fall in the arc resistance to extinction as the pulsing frequency is increased.

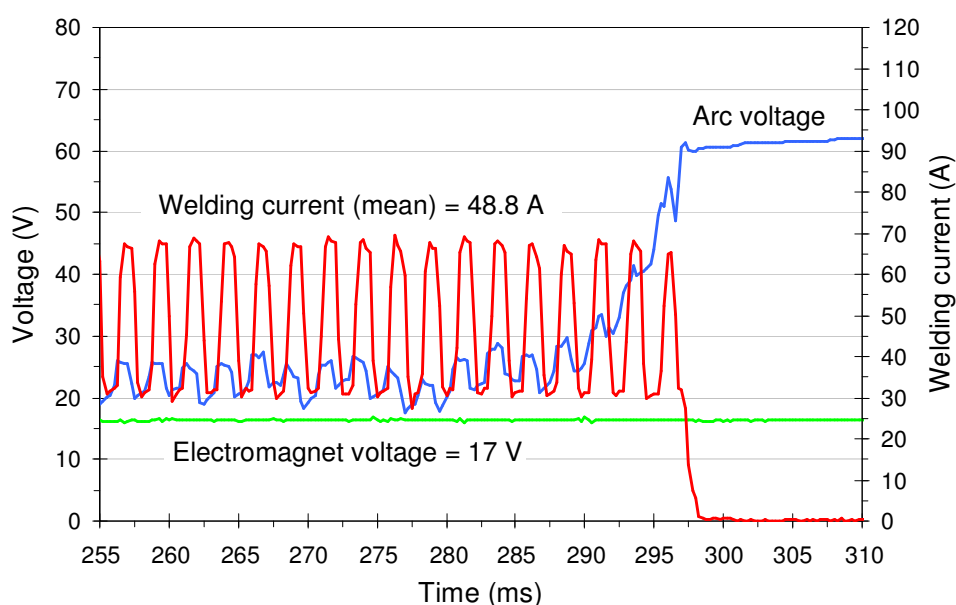


Figure 6.54: A 50 A GTAW arc deflected backwards and extinguished when the welding current is set to pulse at 500 Hz ($I_p = 70$ A; $t_p = 1.0$ ms; $I_b = 30$ A; $t_b = 1.0$ ms; arc length = 10 mm; shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip)
(data acquisition set at 20000 Hz)

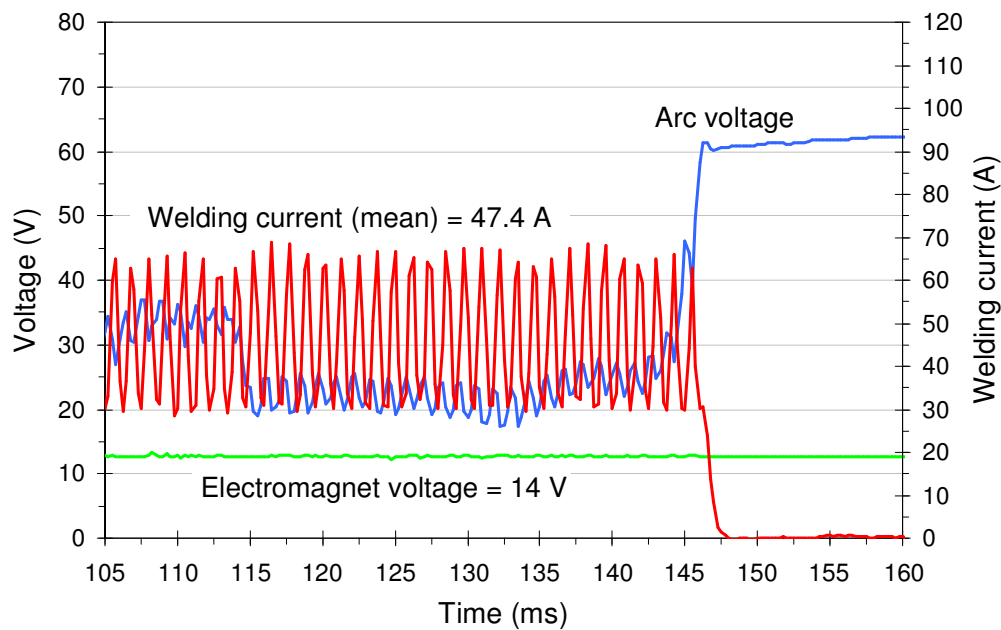


Figure 6.55: A 50 A GTAW arc deflected backwards and extinguished when the welding current is set to pulse at 1000 Hz ($I_p = 70$ A; $t_p = 0.5$ ms; $I_b = 30$ A; $t_b = 0.5$ ms; arc length = 10 mm; shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip) (data acquisition set at 20000 Hz)

Although the difficulty in pointing out an explanation for the fall in the arc resistance to extinction as the pulsing frequency is increased, the findings indicate that high-frequency current pulsing does not seem to improve the stiffness of GTAW arcs when they are subjected to external magnetic fields, which somehow contradicts the literature. In reality, when the literature relates the arc stiffness to the arc pressure over the weld pool, it talks about plasma jet. Obviously, an arc would have better stiffness if its plasma jet was stronger, since the particles that form the arc would get more inertia (velocity) and would offer more power to push the weld pool and improve the penetration, for example. Thus, what seems to take place when the welding current is set to pulse at a very high frequency is a stronger plasma jet and a consequent gain in arc pressure over the weld pool. However, a stronger plasma jet means charged particles travelling at higher speeds. Adding this fact to the presence of an external magnetic field would result in a higher magnetic force (Figure 6.1) in the arc (more arc deflection) and, thus, higher risk of extinction. Therefore, in situations with external magnetic fields, there might be a balance between plasma jet related arc stiffness and magnetic force related arc deflection. This balance could lead to scenario such as the higher the welding current pulsing frequency, the stronger the plasma jet, the higher the charged particles speed, the longer the deflection, the lower the arc resistance to extinction.

This would be a hypothesis to explain the fall in the arc resistance to extinction as the pulsing frequency was increased in the tests carried out above.

As an example of arc extinction in high-frequency current pulsing circumstances, Figure 6.56 shows how an arc is extinguished by an external magnetic field when the welding current is set to pulse at 1000 Hz. It is possible to observe the extinction pattern verified so far; as the arc is deflected, the arc voltage shows some spikes (the arc almost reaches the extinction and recovers) and at some point the arc is extinguished (the welding current drops to zero and the arc voltage rises to the open circuit value). Just before the extinction, it is possible to see how the arc diminishes (gets darker in the 4th frame from left) and grows (gets brighter in the 5th frame from left) apparently for the same deflection. In the 4th frame (base current) the arc seems weaker (deionised) and, as a consequence, the respective arc voltage is high. As the next pulse follows (5th frame), the arc seems stronger (re-ionised) and, as consequence, the arc voltage falls. This pattern repeated through almost all pulses for all tests carried out (see also Figures 6.54 and 6.55), regardless of the pulsing frequency. This behaviour comes in agreement to the fact that the arc ionisation is a consequence of a balance between voltage (strength of collisions between particles) and current (number of collisions between particles). This is also evidence that the arc extinction is a thermic-related phenomenon (the arc “prefers” to be extinguished in lower current values, that is, when the arc is “colder”).

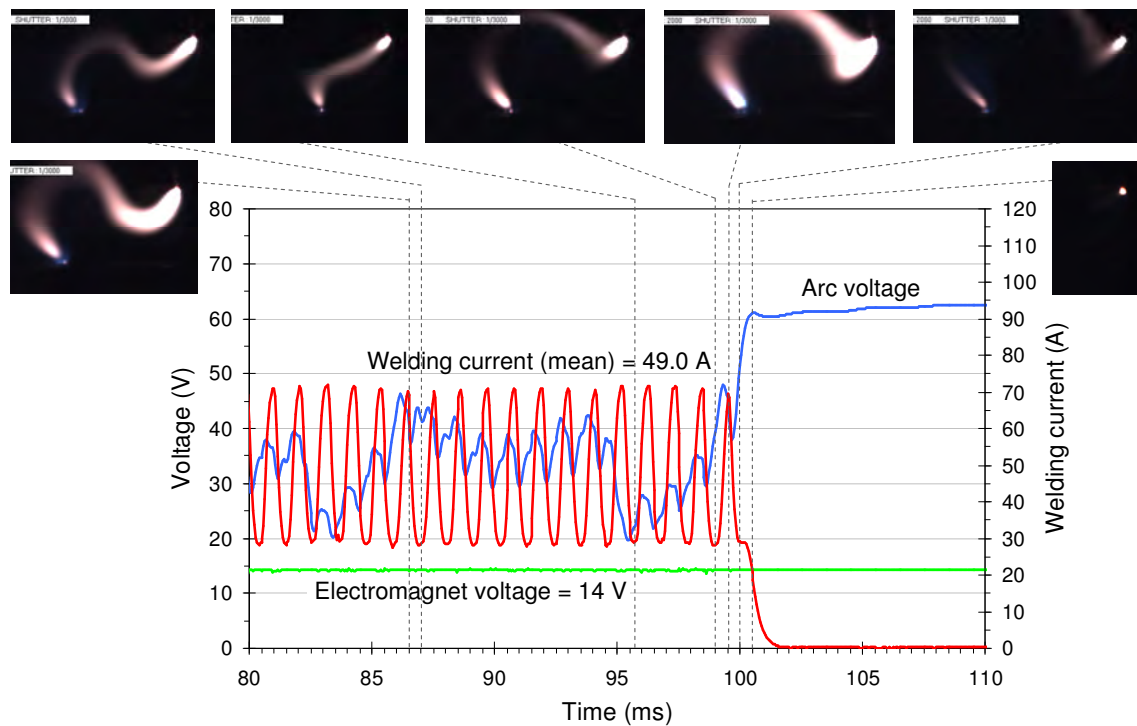


Figure 6.56: A 50 A GTAW arc deflected backwards and extinguished when the welding current is set to pulse at 1000 Hz ($I_p = 70$ A; $t_p = 0.5$ ms; $I_b = 30$ A; $t_b = 0.5$ ms; arc length = 10 mm; shielding gas = Ar at 14 l/min; torch angle = 90° ; electrode: EWTh-2, 2.4 mm, 30° tip) (as the data acquisition was set at 20000 Hz and the images recorded at 2000 Hz, the synchronisation was carried out considering 1 image per each 10 data points)

Figure 6.57 shows arc voltage values at the moment the arc is blown out for different current pulsing frequencies. The values were concentrated in the upper region in the arc voltage range defined in Figure 6.39. Further tests would be necessary to reveal a reason for this behaviour or to verify if it was just a coincidence.

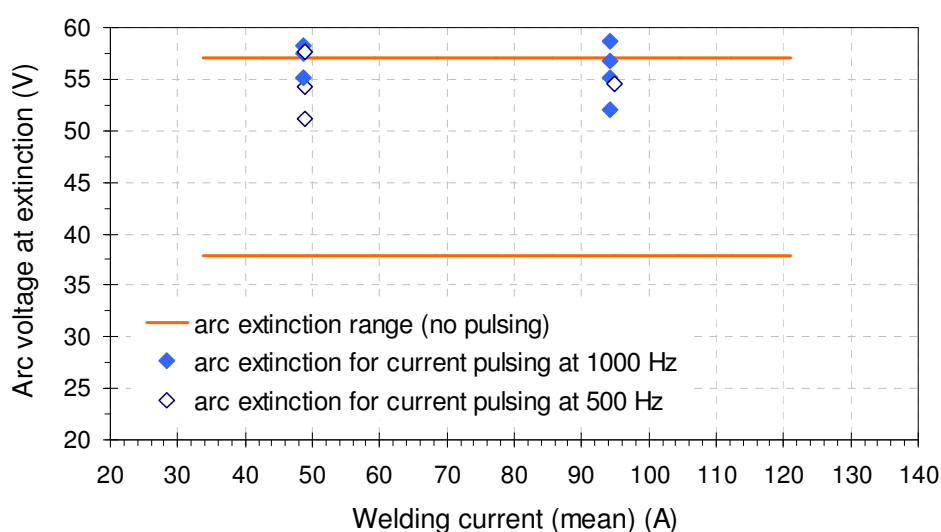


Figure 6.57: Arc voltage values at the moment the arc is blown out for different current pulsing frequencies

6.3.5 Welding current influence (arc deflected forwards)

In order to verify whether the arc resistance to extinction is dependent on the arc direction of deflection or not, the current flowing through the arc was varied for a constant arc length (10 mm) with the arc being deflected (and so blown out) forwards. For each current value tested, the voltage applied to the electromagnet was varied at 1 V steps in order to verify if the edge where the GTAW arc starts to be blown out would be modified in relation to the tests with the arc being deflected (and so blown out) backwards. Table 6.5 shows the current values evaluated and the respective magnetic flux densities needed to cause the GTAW arc extinction in each case. Figure 6.58 shows how the arc extinction edge curve changes when the arc is deflected forwards.

Table 6.5: Welding current values evaluated and respective magnetic flux densities needed to cause the GTAW arc extinction (arc deflected forwards) (arc length = 10 mm; shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip)

Set current (A)	Mean actual welding current (A)	Coil Voltage (V)	Magnetic flux density at the arc extinction edge (mT)
40	42.3	14	2.06
80	78.9	22	3.29
120	111.3	31	4.68

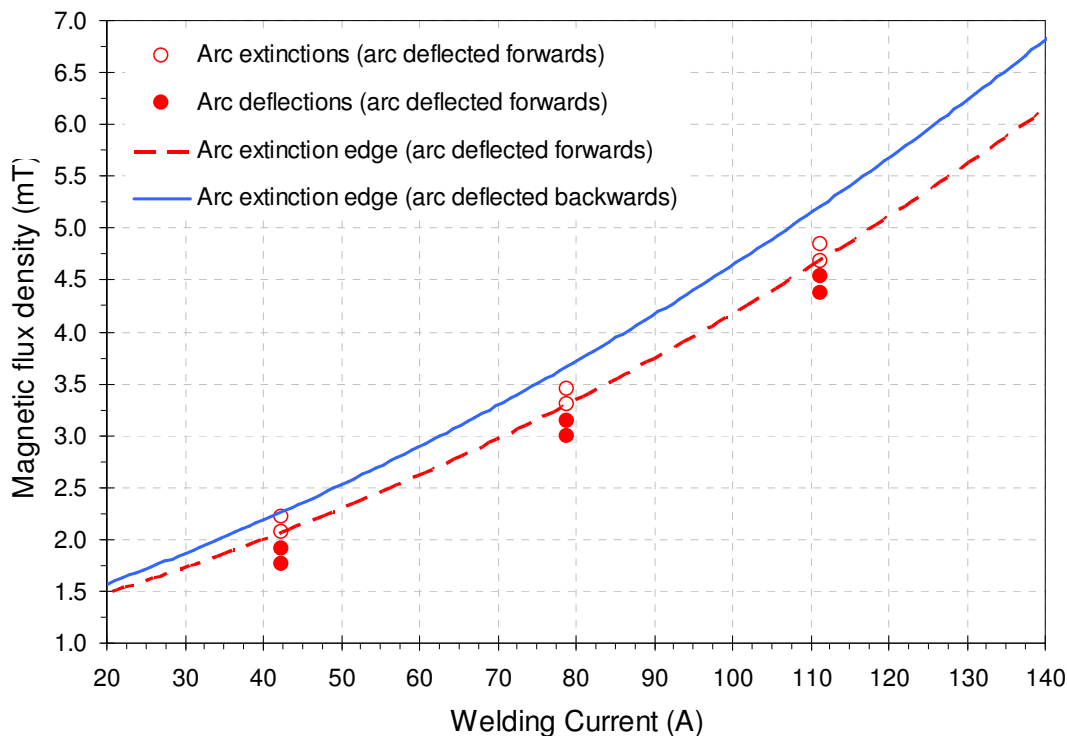


Figure 6.58: Relationship between welding current and resistance to extinction offered by the GTAW arc when it is deflected forwards (arc length = 10 mm; shielding gas = Ar at 14 l/min; torch angle = 90°; electrode: EWTh-2, 2.4 mm, 30° tip)

Compared to the situation in which the arc was deflected (and so blown out) backwards, the arc extinction edge curve is slightly displaced (lowered) if the arc is deflected (and so blown out) forwards instead. This displacement becomes even more pronounced as the current flowing through the arc is increased. There seems to be no straightforward explanation for this fact. However, it could be something related to the interaction between the arc and the weld pool and/or plate, since the condition of the surface where the arc hits the plate, as it is deflected and so blown out, might be different for each case; molten metal (high temperatures) when the arc goes backwards and solid metal (“low” temperatures) when the arc goes forwards. The more pronounced effect at high current levels might be related to higher temperature differences between the regions ahead and under the arc in this case.

As an attempt to clarify any reason for the displacement in the arc extinction edge curve, Figure 6.59 shows an 80 A arc being blown out when it is deflected forwards. As a comparison basis, Figure 6.60 presents an arc at the same current being blown out when it is deflected backwards. Both extinctions followed similar patterns (typical GTAW arc extinction observed so far). However, if a closer look is taken (Figure 6.61) just after the extinction, it seems that the situation with the arc deflected forwards had the plate surface surrounding the arc “colder” (less arc ionisation) than the situation in which the arc was deflected

backwards (more arc ionisation). Despite working with the visible light emitted from the arc (risk of misinterpretation), it is reasonable to think in that line, since the heat from the plate close to the arc may contribute to keep the arc ionised, thus, with more resistance to extinction.

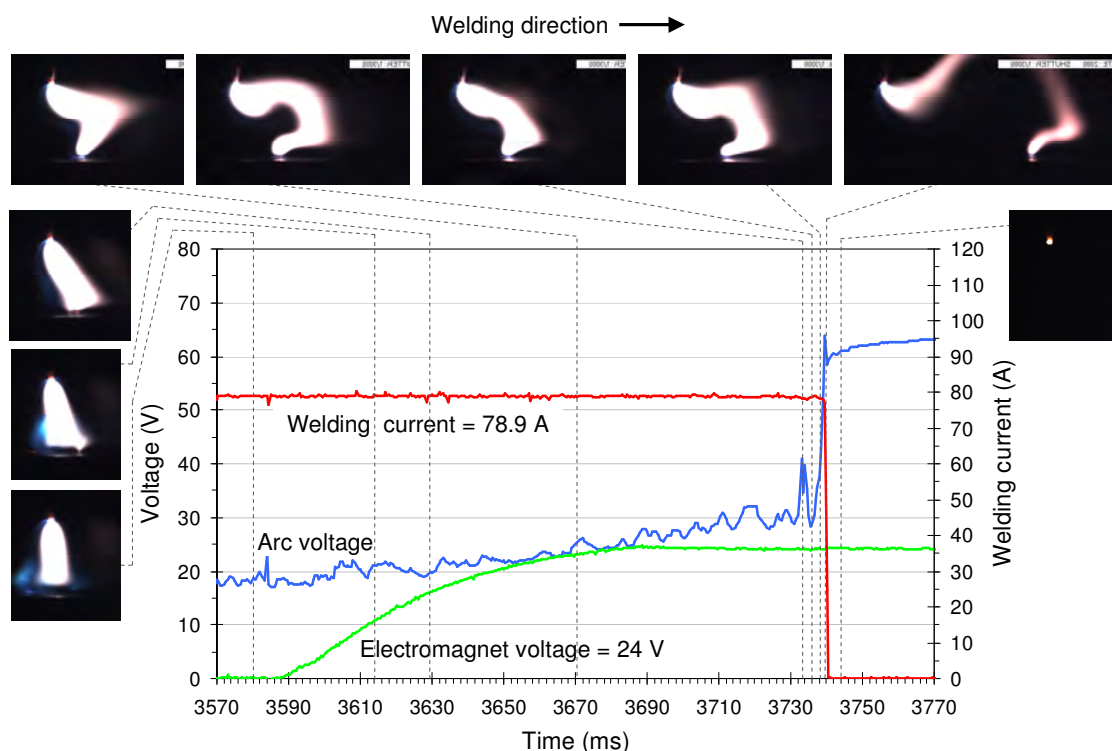


Figure 6.59: An 80 A GTAW arc extinction when it is deflected (and so blown out) forwards (arc length = 10 mm; shielding gas = Ar at 14 l/min; electrode: EWTh-2, 2.4 mm, 30° tip) (data and image acquisition synchronised at 2000 Hz)

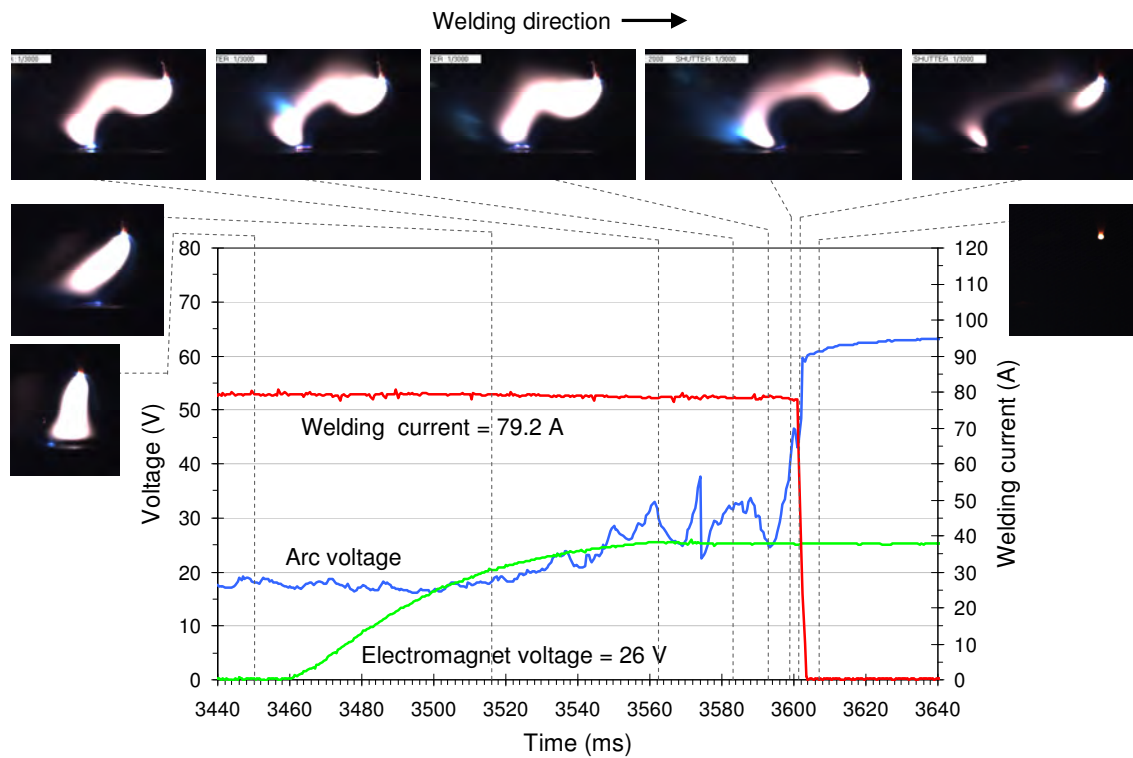


Figure 6.60: An 80 A GTAW arc extinction when it is deflected (and so blown out) backwards (arc length = 10 mm; shielding gas = Ar at 14 l/min; electrode: EWTh-2, 2.4 mm, 30° tip) (data and image acquisition synchronised at 2000 Hz)

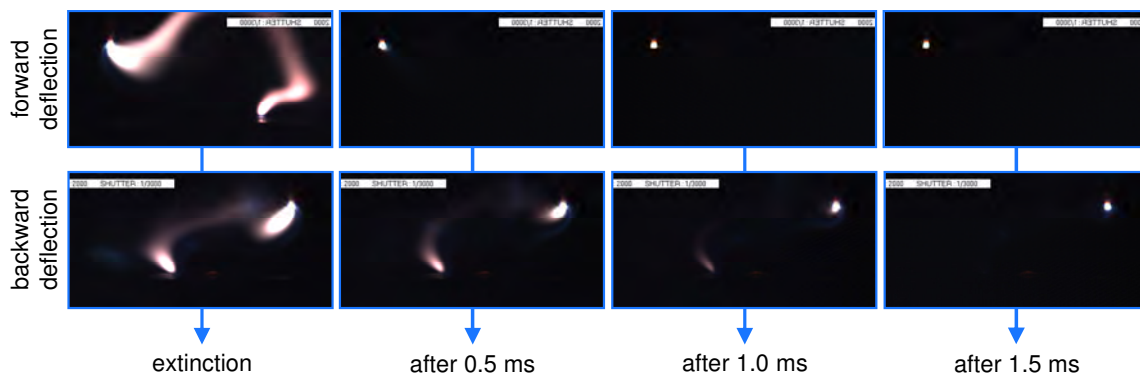


Figure 6.61: Comparison between extinctions of arcs deflected forwards and backwards

Figure 6.62 shows arc voltage values at the extinction moment when the arc is deflected forwards. The fact of having the arc deflected forwards does not seem to have any effect on the arc voltage the extinctions take place. The values were randomised and also tended to fit in the arc voltage range defined in Figure 6.39.

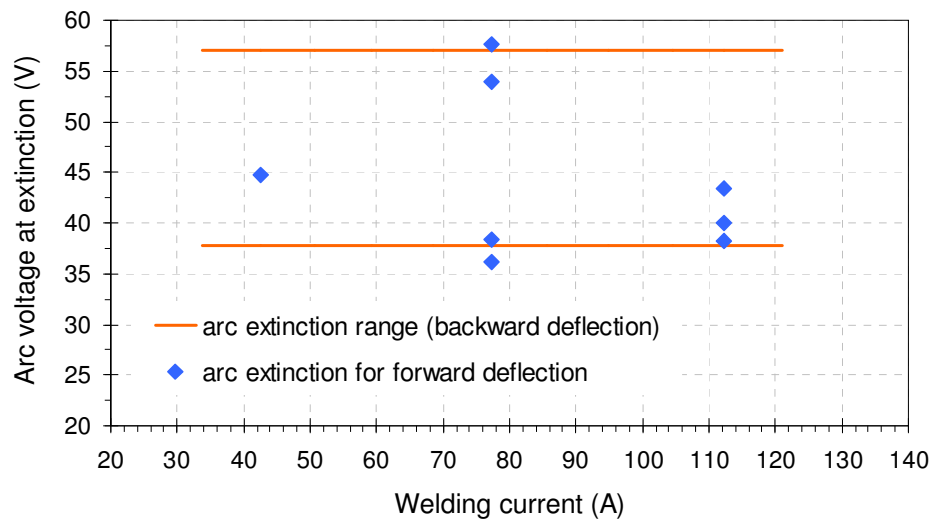


Figure 6.62: Arc voltage values at the moment the arc is blown out by forward deflection

6.4 Considerations on the Arc Extinction Process

As observed from high-speed filming, all arc extinctions occurred at the middle of the plasma column. Taking this fact into consideration, a model is proposed to explain the phenomenon. Let us start from Figure 6.63, which presents a scheme for the balance of energy in a GTAW arc plasma column environment. The plasma column (arc) exists if the total heat generated in and entering into the plasma column matches the heat leaving this arc region (Eq. (6.6)). The loss of heat at the plasma column takes place by advection, diffusion and radiation. However, it is common to find references to convection, conduction and radiation, which would be, to some extent, incorrect, since convection happens by both heat advection (due to movement of gas, natural or forced) and heat diffusion (also called conduction). One can expect a low diffusion heat transfer in Plasma. Thus, it would sound better to say that the loss of heat at the plasma column takes place mainly by advection and radiation. The advection term here accounts for the heat loss due to the shielding gas flow (there is a difference of velocity between the gas flow and the plasma jet) and for the heat loss due to the movement of matter inside the arc (caused by the plasma jet). A fraction of the heat lost by advection goes to the plate. In terms of contribution to the plasma column heat losses, as cited by Richardson (1989) and Allum (1983), the heat loss by convection is the most significant. However, there are controversies, and Tanaka and Lowke (2007), for instance, mention radiation as the predominant heat loss mechanism in the plasma column.

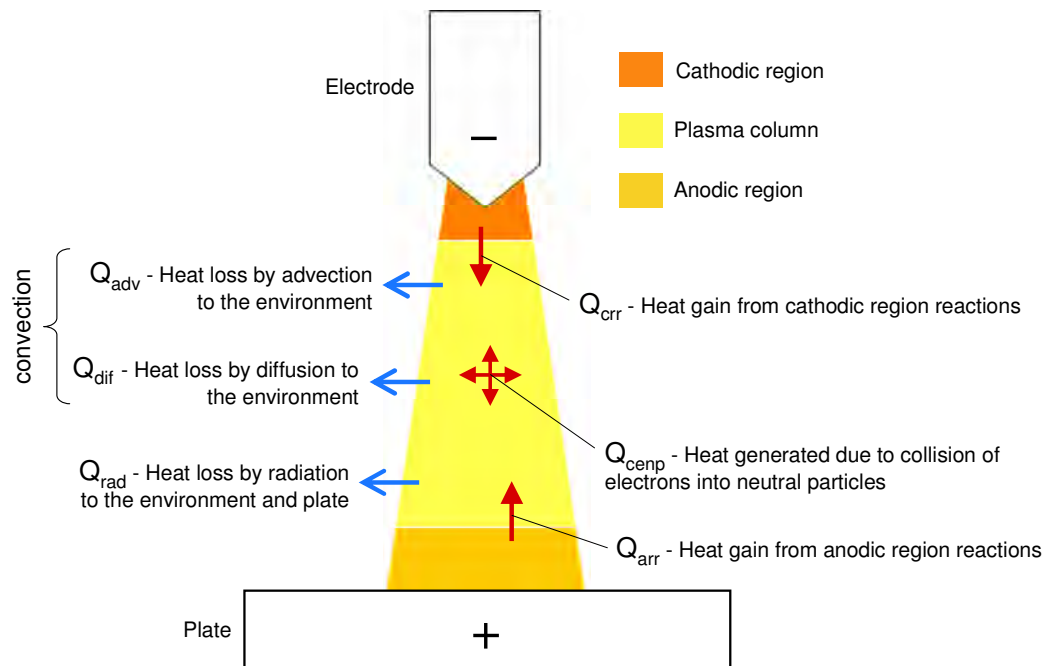


Figure 6.63: Schematic heat balance at the plasma column of a GTAW arc

$$Q_{crr} + Q_{cenp} + Q_{arr} = Q_{adv} + Q_{dif} + Q_{rad} \quad (6.6)$$

According to the proposed model, the arc resistance to extinction is controlled by the deionisation and re-ionisation processes, which occur simultaneously and constantly during welding arc burning. Plasma column deionisation is due to energy lowering of atoms that happens as a consequence of heat losses. Re-ionisation takes place as a result of inelastic shocks between travelling electrons and non-ionized particles (including the deionised ones) along the arc. The shocks transfer energy to the particles, enabling the matter to change from local temperature to the ionised state. The more energy needed by the atom to become ionised (which depends on some plasma characteristics, such as ionisation potential, specific heat, etc.), the higher the difference of potential (DoP), popularly called by voltage, required. In addition, the smaller the number of electrons travelling (lower current), the higher the DoP required (not only as a consequence of a smaller number of shocks, but also because a reduction in the input heat from the anodic and cathodic areas, which turns lesser for lower currents).

When the arc is lengthened for any reason, such as magnetic deflection, its superficial area enlarges and, consequently, the heat loss increases. It is important to point out that to consider the arc as a solid conductor, as in general meaning, might be an imprecise approach. In a solid conductor, the electrical resistance is linked to the difficulty for movement of electrons through its structure (the larger the cross section area, the lower the

DoP). In plasmatic means (arc), on the other hand, it seems to be related mostly to the needs for re-ionisations (the larger the cross section area, the higher the DoP). Thus, the rise of voltage (DoP) as the arc is deflected is due to the necessity of increasing its re-ionisation level to compensate for an increasing deionisation process.

In conclusion, a likely explanation for the arc extinctions is based on:

- During the elongation of the arc, its superficial area increases proportionally and more voltage (DoP) is demanded;
- If the power source is set at constant voltage (static characteristic curve), the welding current takes values progressively lower (less shocks of electrons). As the power source cannot provide higher voltage, the arc is not able to be sustained by the low number of low potential inelastic shocks (low current and low voltage);
- If the power source is set at constant current (static characteristic curve), the welding current is kept at the same value (same likelihood of collisions), regardless of the voltage demanded by the arc. As the power source has a limit to provide voltage (open-circuit value), at a certain length the arc is not able to be sustained by the potential energy of the inelastic shocks anymore;
- One way or another, when the arc is lengthen beyond the steady state conditions, its radius becomes shorter (narrower arc). This is a natural geometric rearrangement of the arc looking for less energy to be sustained (the narrower the conducting column, the lesser the needs of DoP, since the arc superficial area, and the deionisation process, decreases);
- When this narrowing reaches its critical size, the arc is extinguished, usually before reaching null current (constant voltage power source) or the open-circuit voltage (constant current power source);
- The arc extinction happens at the middle of the arc column, in where the heat availability is the lowest, in contrast to the electrode and plate vicinities.

Thus, considering that the arc is blown out due to excessive heat loss (the heat balance is broken) in the plasma column, the influence of welding factors, such as current and arc length, on the resistance to extinction can be better understood.

In the case of the welding current, for instance, this factor influences the heat generated or entering the plasma column (heat input terms). Considering the slightly parabolic arc extinction edge curve shape defined by the welding current (Figure 6.27), it seems that current linearly related heat terms are more pronounced. It is quite reasonable to think in that way, since the heat produced in the cathodic region (current linearly dependent)

represents most of the heat in the arc (highest temperatures close to the electrode) and great part of this heat is transferred by convection and radiation to the plasma column.

Regarding the influence of the arc length, this factor influences the output heat terms, since changes in arc length imply in changes in the arc superficial area. As any arc heat loss is superficial area dependent (quadratic relationship), any increase in the arc length implies in an increase in the plasma column heat loss by convection and radiation.

In relation to the voltage range (37 to 57 V) at which all the GTAW arcs were blown out, it might be because the arcs achieved a region in where the relationship between their voltage and current is unstable and unsustainable. At this region the arc characteristic would be lost. Figure 6.64 shows GTAW arc characteristics for various arc lengths with the region of extinction highlighted.

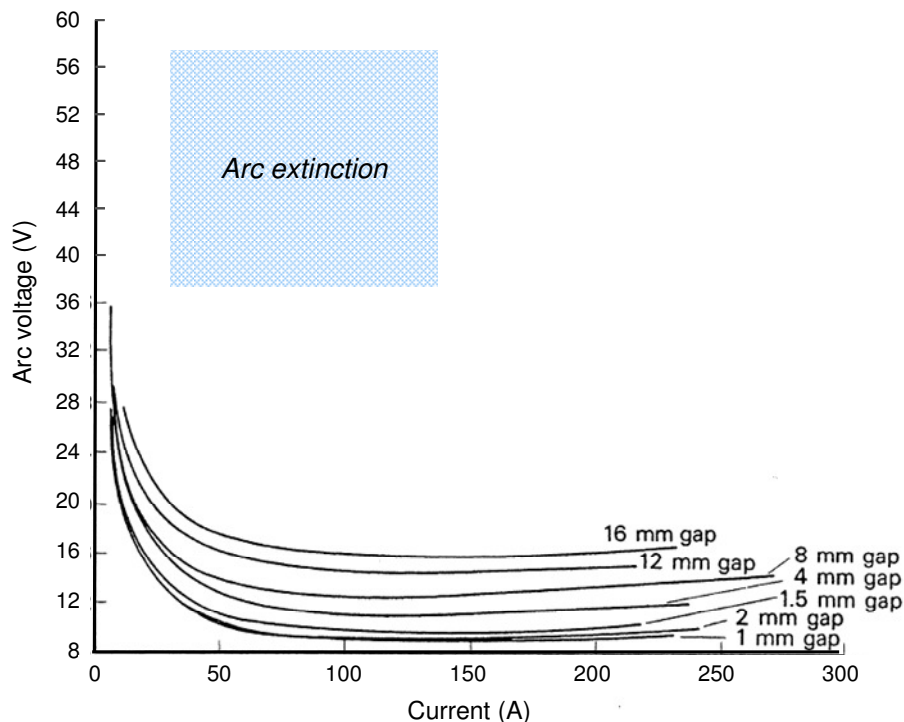


Figure 6.64: GTAW arc characteristics for various arc lengths (gaps) using argon and including the region in which all the arc extinctions took place (after LANCASTER, 1986)

6.4.1 The case of tandem GMAW arcs

Extrapolating the findings regarding the interruptions in GTAW arcs to arcs in tandem GMAW, it is possible to make some comments. As seen previously in Figures 2.21 and 4.40, for tandem GMAW, the number of interruptions in the trailing wire grows and falls as the inter-wire distance is increased. The explanation for this fact could be a balance that takes

place between the magnetic force effect (deflection) and the heating caused by the other arc (Figure 6.65). The closer the deflected arc to the other arc the strongest the magnetic field (the deflection and risk of interruption are increased). However, it seems that for short inter-wire distances this effect is overcome by the heating provided by the other arc, which contributes to keep the deflected arc ionised. As the inter-wire distance is increased this heating decreases and the contribution of the magnetic force exerted by the other arc prevails. It is worth saying that it does not mean that necessarily one arc heats the other, but the heat from one arc can certainly minimise the heat loss of the other one (the lower the temperature gradient, the lower the heat flow).

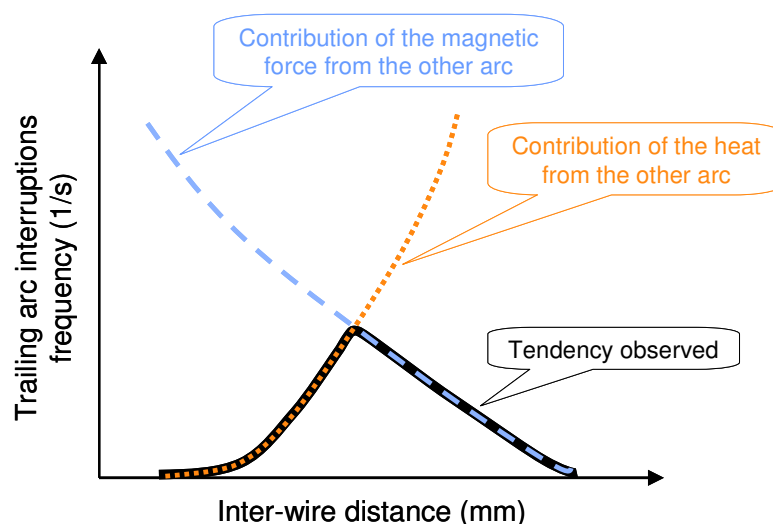


Figure 6.65: Schematic (and didactic) balance between the effects of the magnetic force and of the heat from the leading arc on the tendency for trailing arc interruptions in tandem pulsed GMAW (based on the results presented in Figures 2.21 and 4.40)

Continuing with the extrapolation to tandem pulsed GMAW arcs, the effect of the current in increasing the arc resistance to extinction is evident in the effect of the delay between the current pulses as showed previously in Figures 2.26 and 4.36. As Figure 6.66 shows, as the delay is decreased the number of trailing arc interruptions falls. Considering the situation when the trailing arc deflection is more intense (leading arc current pulse time), the longer the trailing arc remains at a high current level (trailing arc current pulse time) the better (fewer extinctions). As the trailing arc is deflected by the leading one and it has its length increased, which leads to loss of heat and higher risk of extinction/interruption, the trailing arc current pulse increases its own heat generation, which counteracts the loss of heat and the consequent risk of being blown out.

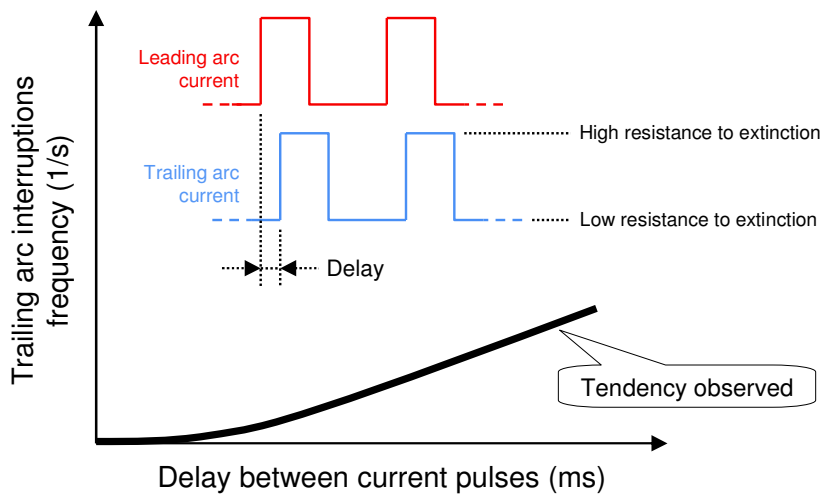


Figure 6.66: Schematic effect of the delay between the current pulses on the tendency for trailing arc interruptions in tandem pulsed GMAW (based on the results presented in Figures 2.26 and 4.36)

Considering the model for arc deflection in tandem GMAW presented in Figure 2.24, it is possible to add more comments regarding the effect of the synchronism between the current pulses. Figure 6.67 shows the deflection of arcs in tandem GMAW, calculated by using such model, in function of the welding current for different synchronism approaches. For the out-of-phase approach, it is possible to see that the trailing arc deflection is the highest when the leading arc current is applied, which coincides with the moment the trailing arc has low resistance to extinction (base current level). By using an almost-in-phase approach (shortening the delay between the pulses of current of each arc), the time in which the trailing arc remains in this situation (intense deflection and low resistance to extinction) is reduced; at the same time the trailing arc resistance to extinction is increased by raising its current level, the deflection of such arc is reduced. An ideal situation is achieved for an in-phase synchronism approach. In this case, the arc deflection is kept at a low level all the time

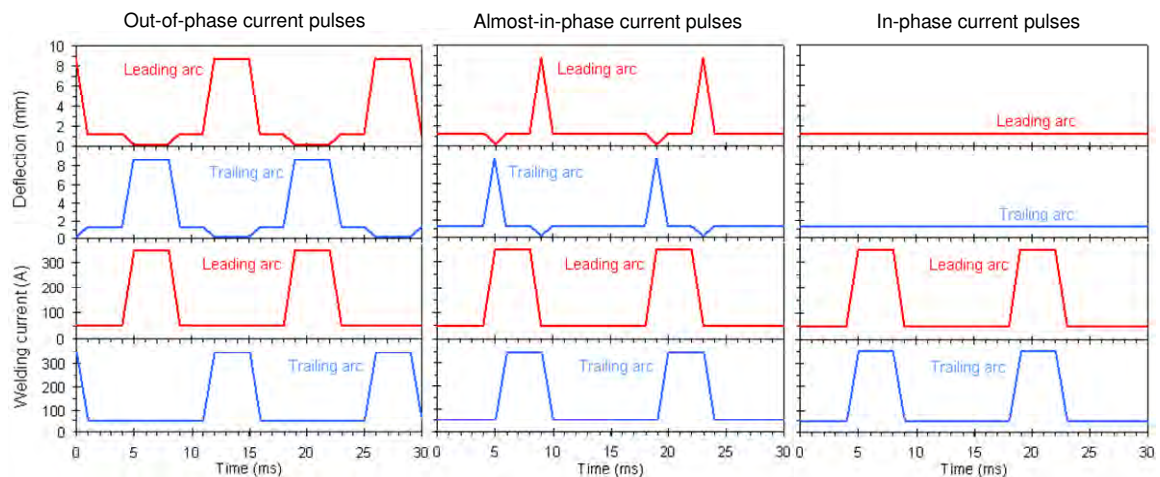


Figure 6.67: Calculated deflection of the leading and trailing arcs depending on the synchronism for the current pulses utilised in tandem pulsed GMAW (calculation based on 5 mm long arcs and with a 10 mm inter-wire distance) (see Figure 2.24)

Thus, two factors seem to act in determining the trailing arc interruptions in tandem pulsed GMAW:

- The deflection of the trailing arc, which depends on the trailing arc current and length, on the leading arc current and on the inter-wire distance; and
- The heat generated and “absorbed” by the trailing arc, which are dependent, respectively, on the trailing arc current and on the leading arc current and inter-wire distance.

As just said, both these factors are related to the current and a balance between them must be established to avoid the interruptions. It is a matter of how much current and when it is applied (synchronism approach).

Through all the experiments carried out during this investigation on arc interruptions, potential effects of a possible induced current in the arc, resulted from variations in the magnetic flux density caused by the other arc (mutual induction) or by the electromagnet or even resulted from the pulses of current in the arc (self-induction), were not considered or discussed. No traces of induced current were noticed in the electrical transients.

6.5 General Comments

In situations in which welding arcs are affected by magnetic fields (tandem GMAW, magnetic arc oscillation, etc.), they can be certainly extinguished/interrupted if the magnetic flux density is high enough.

The influence of some welding parameters on the arc extinction process can be summarised as:

- The higher the electrical current flowing through the arc, the more the arc resists to the extinction;
- If the arc length is shortened, its resistance to extinction is increased;
- At least for the angles tested and in the case of GTAW arcs subjected to external magnetic fields, if the torch (arc) angle is set in order to “push” the weld pool, it increases the arc resistance to extinction;
- Contradicting the literature, the utilisation of high-frequency current pulsing in general tends to decrease the arc resistance to extinction;
- The arc resistance to extinction is slightly decreased if the arc is deflected (and so blown out) forwards instead of backwards in relation to the welding direction.

The arc voltage values at the extinction moments do not seem to be dependent neither on the magnetic field externally applied nor on the welding current level used. However, all the arcs tended to be extinguished inside an arc voltage range (37 to 57 V).

Hypothetically, the arc is blown out due to an excessive heat loss as its length is increased in consequence of the deflection. Therefore, the arc extinction would take place if the heat produced in and entering the plasma column became insufficient to balance the plasma column total heat loss.

Extrapolating the findings to tandem pulsed GMAW, two factors seem to act in determining the trailing arc interruptions: the deflection of the trailing arc and the heat generated and “absorbed” by the trailing arc. Both these factors are related to the current and a balance between them must be established to avoid the interruptions. Given a configuration of GMAW arcs (length, inter-wire distance, etc.), the minimisation/elimination of interruptions is a matter of how much current and when it is applied (synchronism approach).

CHAPTER XII

CONCLUSIONS

In order to find new alternatives for welding processes, three approaches for tandem GMAW, at relatively low currents, were developed based on pulsed and controlled short-circuit modes (current waveform control). A new approach for hybrid welding combining LBW with tandem GMAW was also tried. A system consisted of a low cost back light and a software for image/data synchronisation and analysis was developed to assist in the assessment of such approaches.

In relation to the use of pulsed current waveform in both wires, the conclusions were as follows:

- The software devised for this version of tandem GMAW was able to control the pulsing parameters (current waveform) for both wires;
- Disturbances and interruptions, mainly in the trailing arc, took place due to arc interaction (attraction) and instability of cathode spots;
- It was verified, at least for low levels of mean current, that the pulses of current from the leading and trailing wire needed to be almost-in-phase (very small delay time) in order minimize abnormal voltages (disturbances) and avoid arc interruptions in the trailing wire, regardless of the plate surface (scaled or not);
- The tandem pulsed GMAW with low levels of mean current was the only approach that showed conditions to be applied in joint situations.

In relation to the use of controlled short-circuit waveform in both wires, the following conclusions could be pointed out:

- The software devised for this version of tandem GMAW was able to control the parameters (current waveform) for both wires;
- The welding process was highly unstable because of the intense interaction between the arcs and the weld pool. This interaction led to low stability indexes for both wires and to trailing arc disturbances and interruptions.

In relation to the use of controlled short-circuit and pulsed waveforms in the leading and in the trailing wire, respectively, the conclusions were as follows:

- The software devised for this version of tandem GMAW was able to control the parameters (current waveform) for both wires;
- Despite the attempts to synchronise the processes used in each wire in order to avoid or minimise the occurrence of interruptions in the trailing arc, the welding process, as whole, had a very narrow operational window, which made any application prospect unlikely at this stage.

Regarding the application of Laser beam to aid the tandem GMAW (pulsed mode) process, the following conclusions could be made:

- Regardless of welding with “almost-in-phase” or out-of-phase current pulses for the tandem GMAW process, the Laser beam had a positive effect on the visual aspect of the weld beads produced (the higher the Laser beam power the better);
- The hybrid process approach was able to increase significantly the maximum welding travel speed or penetration depth on bead on plate tests in comparison to tandem GMAW (pulsed mode);
- The Laser beam worked better if located half way between the leading and trailing wire and an inter-wire distance of 10 mm promoted the best welding results;
- The position of the Laser beam focus point in relation to the plate surface did not affect the weld bead profile.

In order to understand the mechanisms behind the arc interruptions in tandem GMAW, an electromagnet was devised and, to simplify the tests, GTAW arcs were subjected to sudden magnetic fields produced by this equipment. Thus, in relation to the effect of external magnetic fields on welding arc stiffness, the conclusions were as follows:

- In situations in which welding arcs are affected by magnetic fields (tandem GMAW, magnetic arc oscillation, etc.), they can be certainly extinguished/interrupted if the magnetic flux density is high enough;
- The higher the electrical current flowing through the arc, the more the arc resists to the extinction (higher stiffness);
- The shorter the arc length, the more the arc resists to the to extinction;
- If the torch (arc) angle is set to “push” the weld pool, it increases the arc resistance to extinction in the case of GTAW arcs deflected backwards;
- At least for the frequencies used, the utilisation of high-frequency current pulsing decreased the arc resistance to extinction;
- The arc resistance to extinction is slightly decreased if the arc is deflected (and so blown out) forwards instead of backwards in relation to the welding direction;
- The arc voltage values at the extinction moments are not dependent, neither on the magnetic field externally applied, nor to the welding current level used. However, all the arcs tended to be extinguished inside an arc voltage certain range;
- Hypothetically, the arc is blown out due to an excessive heat loss as its length is increased in consequence of the deflection. Therefore, the arc extinction would take place if the heat produced in and entering the plasma column became insufficient to balance the plasma column total heat loss;
- Extrapolating the findings related to GTAW arcs to tandem pulsed GMAW, two factors act in determining the trailing arc interruptions: the deflection of the trailing arc and the heat generated and “absorbed” by the trailing arc. Both these factors are related to the current and a balance between them must be established to avoid the interruptions. Given a configuration of GMAW arcs (length, inter-wire distance, etc.), the minimisation/elimination of interruptions is a matter of how much current and when it is applied (synchronism approach).

CHAPTER XIII

RECOMMENDATIONS FOR FUTURE DEVELOPMENTS

Based upon the outcomes of this work, the following issues should be addressed in the future.

As it was the only approach that showed to have an application condition amongst the assessed ones, the tandem pulsed GMAW with low levels of mean current should be applied in joint situations, to verify if it can be feasible to improve the welding speed of root runs and in different welding positions, where low energy input is demanded.

Considering the difficulty presented by the tandem GMAW process with both wires operating in a controlled short-circuit mode, the recommendations for future developments might be as follows:

- Using a Laser beam between the wires to verify any further improvement in the process. The extra heat source might make the concentration of molten metal lower and uniform and, thus, less influent on the short-circuiting period (better stability);
- Using short inter-wire distances as a way to avoid the concentration of molten metal before the trailing arc, which might improve the stability of the process;
- Variables like wire diameter, shielding gas, etc., and other combinations of welding parameters should be further explored in conjunction with high-speed filming to determine whether the process can be feasible or not.

Considering the complexity of the combination of controlled short-circuit GMAW and pulsed GMAW as a tandem process, further investigations with different parameters and welding conditions, such as thinner wires, should be tried before investing in more modifications in the control program. The controlled short-circuit waveform approach used in

this work showed to work better (higher stability index) in single GMAW with a 1 mm wire at the time it was devised.

Despite the positives outcomes regarding the tandem pulsed GMAW process aided by Laser beam, a more detailed investigation is suggested to evaluate the process and its variables in joint situations, different levels of GMAW energy and transfer modes, higher Laser beam power levels, different materials and thickness, etc. Application in root runs and a cost assessment are also recommended.

The following suggestions are made as complement to the study on the effect of magnetic fields on arc stiffness:

- Verifying if the resistance to extinction of GTAW arcs changes with variable polarity welding. In this case, the arc resistance to extinction is expected to decrease significantly, since the current drops to zero every time the welding polarity changes;
- Verifying if the arc resistance to extinction changes if frequencies of current pulsing as high as 5000 Hz are applied to GTAW arcs. The effect of frequencies around this value on electrical arcs is more pronounced. Power sources dedicated to high-frequency pulsed welding will be required;
- Varying the length of GTAW arcs continuously (by means of an electrical-mechanical device, for example) for various current levels and compare the arc voltage value at the moment the arc extinction takes place to the values at which the GTAW arcs were extinguished by an external magnetic field in this work. If the values are similar, there will be another indication that the arc is blown out in the presence of a magnetic field due to an excessive deionization (loss of heat) as a consequence of its length rise (superficial area increase);
- Verifying if PAW (Plasma Arc Welding) arcs offer any gain in resistance to extinction in the presence of external magnetic fields, since they are considered to have elevated stiffness;
- Verifying if the weld pool affects the arc deflection in the case of GMAW as a way to better understand what happens in tandem GMAW. The presence of a bulk of molten material underneath the trailing arc could be a factor that leads to more problems in this arc, since it can change the magnetic field profile;
- Assessing the influence of the plate surface condition in the arc resistance to extinction in single GMAW using external magnetic fields. Clean plates (free from mill

scale) should be compared to unclean plates (with mill scale) to better evaluate the plate surface condition effect;

- Verifying if the plate material influences the arc resistance to extinction. A comparison between ferritic stainless steel (ferromagnetic) and austenitic stainless steel (paramagnetic) is suggested to check if the plate material changes the profile of the external magnetic field and, thus, the arc resistance to extinction;
- Using the tandem GMAW with the arcs side by side, instead of following each other, to see if there is any change in the occurrence of disturbances and/or interruptions. This arrangement would give a kind of symmetry to the arcs and would help in understanding why the trailing arc experiences much more disturbances and/or interruptions;
- Evaluating the effect of the shielding gas on the resistance to extinction offered by GTAW and/or GMAW arcs. In the case of GTAW arcs, the helium content in the argon could be evaluated in terms of heat conductivity and mass density. In the case of GMAW arcs, the CO₂ content could be evaluated to establish a comparison with the results found in the literature;
- Synchronising a pulsed external magnetic field to the pulsed current waveform in single GMAW and make an assessment of the arc resistance to extinction. This approach would be very similar to tandem GMAW and effects of variables like the delay between the pulsed current and the pulsed external magnetic field, in other words between the pulsed currents in tandem GMAW, could be better evaluated.
- Due to the expected presence of induced current, resulted from variations in the magnetic flux density in the arc region, an experiment should be developed to measure the current strictly inside this region, since induced currents were not noticed in the electrical transients and may be limited to the arc. Thus, possible effects of this induced current on the arc extinction process could be detected.

CHAPTER IX

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Resumo Estendido

Em função da demanda industrial por produção de baixo custo, eficiente, rápida e confiável, a necessidade de soluções de manufatura sofisticadas e avançadas tem aumentado. Em face desta demanda da indústria atual por produtividade, o setor de fabricação tem procurado por novos, e mesmo não tão novos, processos. A meta tem sido superar limitações relacionadas à manufatura dos processos atuais. Esta meta não é diferente para a soldagem e somente pode ser alcançada com soluções envolvendo entendimento dos fenômenos envolvidos. Assim, soluções para desafios de fabricação relacionados à soldagem têm sido alcançadas a partir do desenvolvimento de novos processos e, especialmente, pelo uso de novos arranjos para processos convencionais.

O objetivo deste trabalho foi, então, avaliar o uso de técnicas e processos combinados como meio de superar limitações de fabricação relacionadas à soldagem. Como forma de atingir este objetivo, versões distintas do processo GMAW duplo-arames foram avaliadas. O potencial para altas velocidades de soldagem do processo com dois arames foi unido à habilidade para controlar a penetração dos modos de transferência por curto-circuito controlado e/ou pulsado. Uma combinação de GMAW duplo-arames e soldagem a Laser também foi avaliada. Em consequência de dificuldades encontradas em GMAW duplo-arames, foi feita uma investigação sobre interrupções de arco utilizando campos magnéticos para apagar os arcos.

Três versões da soldagem GMAW duplo-arames foram desenvolvidas através do controle do formato de onda de corrente por três programas (softwares): um com modo pulsado em ambos os arames, um com modo curto-circuito controlado em ambos os arames e um com modo curto-circuito controlado no arame da frente e modo pulsado no arame de trás. Todos os programas foram capazes de controlar os parâmetros de soldagem em ambos os arames. Entretanto, o processo com os dois arames operando no modo curto-circuito controlado e o processo com o arame da frente no modo curto-circuito controlado e com o arame de trás no modo pulsado foram altamente instáveis por causa da intensa interação entre os arcos e a poça de fusão, o que impede qualquer possibilidade de aplicação dos mesmos em passes de raiz no estágio atual de desenvolvimento dos

programas. Em relação ao processo com modo pulsado em ambos os arames, foram observadas instabilidades e interrupções de arco, principalmente no arame de trás. Estas interrupções de arco levaram a defeitos de falta de deposição e fusão/penetração, já que elas causam pausas na deposição de arame e na fonte de calor. Foi verificado, ao menos para baixos níveis de corrente média, que os pulsos de corrente do arame da frente e de trás precisaram estar quase que em fase (pequena defasagem) para minimizar tensões anormais (instabilidades) e evitar interrupções no arame de trás, não importando a condição superficial da chapa (oxidada ou não). O processo GMAW duplo-arames no modo pulsado em baixos níveis de corrente foi a única opção que mostrou condições de ser aplicada em juntas, podendo ser viável para aumentar a velocidade de soldagem de passes de raiz.

Assim, o processo GMAW duplo-arames em modo pulsado foi escolhido para ser combinado com um feixe de Laser, formando um processo híbrido. O feixe de Laser teve um efeito positivo sobre o aspecto dos cordões de solda produzidos e quanto maior a potência do feixe melhor. Os resultados indicaram que o feixe de Laser é melhor utilizado se colocado no meio da distância entre os arames e uma distância entre arames de 10 mm promoveu os melhores resultados. O processo híbrido foi capaz de aumentar significativamente a velocidade de soldagem máxima ou a profundidade de penetração em testes sobre chapas em comparação ao GMAW duplo-arames em modo pulsado. Para as condições utilizadas, a posição do ponto focal do feixe Laser em relação a superfície da chapa não afetou o perfil do cordão de solda.

Para simplificar a abordagem na investigação sobre as razões para a ocorrência de interrupções de arco em GMAW duplo-arames, arcos GTAW foram submetidos a campos magnéticos repentinos produzidos por um eletroímã construído para deflexão/apagamento de arcos elétricos. Os testes mostraram que em situações nas quais arcos de soldagem são afetados por campos magnéticos (GMAW duplo-arames, oscilação magnética de arco, etc.), eles podem ser certamente extintos (interrompidos) se a densidade de campo magnético for alta o suficiente. Quanto maior a corrente elétrica fluindo através do arco e mais curto o comprimento do arco, mais o arco resiste a extinção. Ao menos para as condições utilizadas, se o ângulo da tocha (arco) é selecionado de forma a “empurrar” a poça de fusão, a resistência do arco à extinção aumenta. A pulsação de corrente em alta-frequência, em geral, diminuiu a resistência do arco à extinção, contrariando a literatura. A resistência do arco à extinção foi levemente reduzida com o arco desviado (e então apagado) em direção ao sentido de soldagem. Os valores de tensão de arco no momento de extinção não pareceram ser dependentes, nem do campo magnético externo, nem do nível de corrente de soldagem utilizado. Entretanto, todos os arcos tenderam a ser extintos dentro de uma faixa de tensão. Um modelo para explicar as interrupções de arco foi proposto baseado no

balanço de calor na coluna de plasma. Baseado neste modelo, o arco é extinto devido à uma perda de calor excessiva à medida que tem seu comprimento aumentado em função da deflexão. Consequentemente, a extinção do arco acontece quando o calor produzido e entrando na coluna de plasma se torna insuficiente para contrabalançar a perda de calor total na coluna de plasma. Extrapolando os resultados relacionados a arcos GTAW para arcos GMAW, dois fatores agem para determinar as interrupções do arco de trás: a deflexão do arco de trás e o calor gerado e “absorvido” pelo arco de trás. Ambos estes fatores são relacionados à corrente de soldagem e um balanço entre eles deve ser estabelecido para evitar as interrupções. Dada uma configuração de arcos em GMAW duplo-arame (comprimentos, distância entre arames, etc.), a minimização/eliminação de interrupções é uma questão de quanta corrente e de quando ela é aplicada (sincronismo).

Conclui-se o trabalho apresentando sugestões para desenvolvimentos futuros.

APPENDIXES

1 MODELS TO DESCRIBE PLASMA JET, ARC TRAJECTORY AND ARC BLOW FORMATION IN ARC WELDING

(IIW DOC. 212-1141-09)

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1. Introduction

Arc welding is one of the most important means of manufacturing. Despite of being widely used, the process correct operation is indispensable to achieve the each day more required quality and productivity. Thus, demands for process improvement appear every day. However, to accomplish with the new applications, a deep knowledge about the concerned phenomena is mandatory for developers. The field of study of these phenomena is known as physics of arc but, unfortunately, due to complexity there are not many specialists in the world dealing with this subject. However, its importance is highlighted by the Study Group 212 ("Physics of Welding") devoted to this matter in the IIW (International Institute of Welding).

On the other hand, books and handouts about arc welding are written aiming to transfer new practices and theoretical knowledge to users. And they have to cite definition and characteristics of some fundamentals, such as plasma jet and arc blow formation. For instance, in the case of arc blow, classical pieces of literature such as AWS Welding Handbook (1991, p.48) do not further explain this phenomenon beyond "the result of magnetic disturbances surrounding the arc". The Lincoln's Procedure Handbook of Arc Welding (2000, p.3.2-1) limits to state that "the magnetic arc blow is caused by an unbalanced condition in the magnetic field surrounding the arc". According to Lancaster (1986, p.215), "arc blow may result from asymmetric current paths in the work-piece close to the arc or from the magnetization of the plate material". In the case of plasma jet, Houldcroft and John (1988, p.12) cite that "the flow of current in the arc results in a magnetic field, which involves the arc and tends to compress it, the so-called 'pinch effect'. Due to the way the arc expands from the electrode to the work-piece, an axial component of the pinch effect happens and it causes the hot ionised gas in the arc to be set in motion from the electrode to the work. This is sometimes called plasma jet and it is responsible for the depression formed in the surface of molten pools at high welding currents". Lancaster (1986, p.128), in turn, declares that plasma jet is an "electromagnetically induced flow of gas in the arc column, which is directed away from the constriction at the electrode".

Nevertheless, when new development is the target, the need of further understating on some basic aspects of welding comes out. Apparently, simple and broadly accepted concepts begin to fall in uncertainty when answers related to another phenomena need to be found. A specific case is the effect of the interaction of two close welding arcs, when one arc

may be even blown out by the other one. In order to understand such interaction, it is firstly necessary to figure out how one single arc interacts with itself. Despite the importance of the above mentioned means of learning, there is a lack of full explanation on certain basic aspects on electromagnetic arc interactions. For instance, what really causes pressure into a compressive environment as an arc column? Or, how can a mass of plasma move away due to magnetic pressure? Is plasma jet the governing factor to direct the arc column? Thus, the objective of this work is to contribute to a further understanding of these topics.

2. A Survey on Plasma Jet and Arc Blow

At first, an e-mail survey was carried out through one month (February 2009) to raise the degree of consensus on the understanding of welding specialists on plasma jet formation and arc blow phenomenon. The survey was based on the fact that all interviewee knew at least the basic concepts about these two matters. The questionnaire was sent to more than 150 people, amongst welding researchers, professors, lectures and post-graduated students, in various countries. As no sampling was used, the authors do not claim any significance to the results. The objective was only to find out whether there are divergences or not.

The two questions and respective alternative answers are as follows. As one can see, there is, to some extent, a degree of orientation in the answer due to the multiple choice approach. On the other hand, the answers were as short as possible to maintain the aim.

Question 1 - It is usually claimed that the plasma jet in arc welding is formed due to a gradient of pressure between the electrode tip and the weld pool. The reason for the pressure at both regions is:

- a) A resulting magnetic field that pushes the bulk of the gas and plasma masses towards the centre line of the arc.
- b) A resulting radial electromagnetic force that pushes the bulk of the gas and plasma masses towards the centre line of the arc.
- c) A resulting radial electromagnetic force that pushes the charged particles of plasma towards the centre line of the arc.
- d) All of them.
- e) It is out of the scope of my knowledge.

Question 2 - Arc blow is a phenomenon that happens during arc welding under some circumstances. The arc deviation path is defined by:

- a) The bulk of plasma mass which changes place due to a gradient of magnetic field (stronger in one side).
- b) The bulk of plasma mass which changes place due to uneven forces created by a gradient of magnetic field (stronger in one side).
- c) A new trajectory of charged particles due to a resulting radial electromagnetic force.
- d) All of them.
- e) It is out of the scope of my knowledge.

Despite the low number of respondents (a total of 27; 1 from North America, 21 from Latin America, 4 from Europe, 1 from Australia and none from Japan), the survey showed some evidences about how people understand the subject. According to Figure 1, there is some consensus around answer “c” for the first question. Nonetheless, 35% of the interviewees gave other answers. Interestingly enough, the authors have not seen yet a clear reference to answer “c” in books. Regarding the question 2, the tendency was quietly the same (the majority believes in answer “b”, but a significant part has other opinion). The outcome of this survey confirms that the subject is not so clear and it justifies the elaboration of a more comprehensive description for the phenomena.

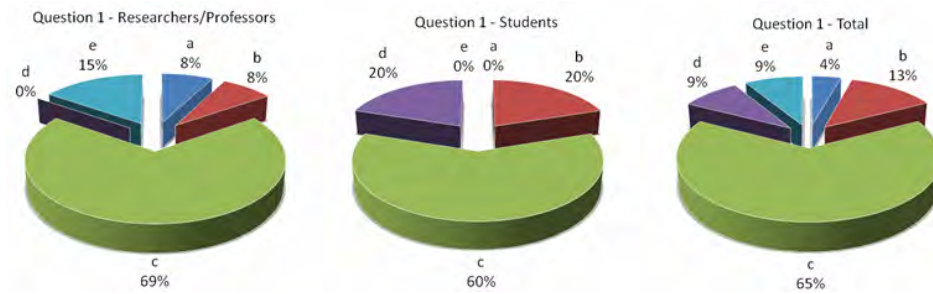


Figure 1: Distribution of the answers for Question 1

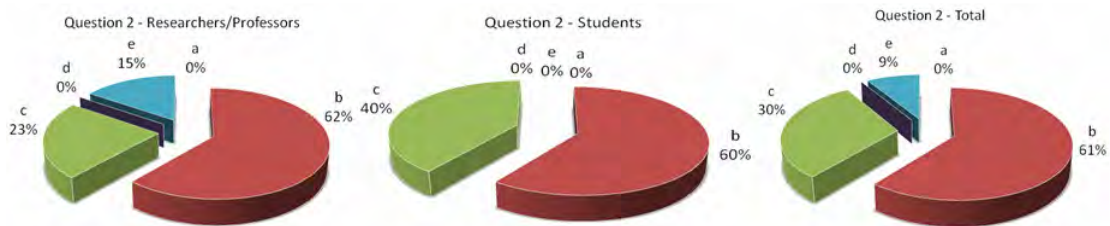


Figure 2: Distribution of the answers for Question 2

3. Magnetic Field Interactions in the Welding Arc

3.1. General concepts

It is already known that the welding arc ionisation process takes place mainly due to energy transfer caused by inelastic collisions of particles (ions and electrons). It is also largely stated that the welding arc does not achieve a complete ionisation. Therefore, the arc is constituted by ionised and non ionised matter.

Before discussing arc trajectory and plasma jet formation in the welding arc, it is worth taking a brief look at the basic electromagnetic effect that governs the phenomenon. If an electrical charge travels inside a magnetic field, it will be subjected to a force with direction and magnitude described by Figure 3. As there is an electrical current flowing through the arc, a magnetic field is induced (Figure 4). Since the arc has a large number of charged particles (ions and electrons), this magnetic field creates a radial force field in the arc.

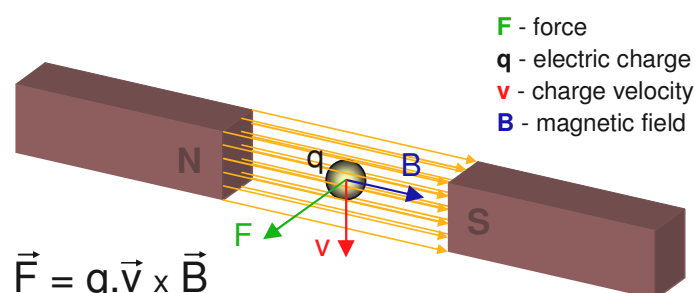


Figure 3: Force produced on a positive electrical charge moving through a magnetic field (if the electrical charge is negative, the force direction points to the opposite way)

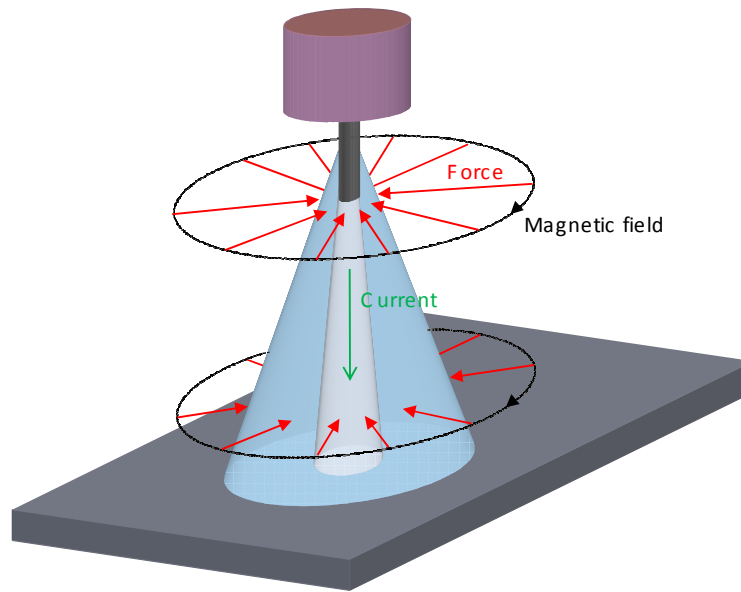


Figure 4: Magnetic field and consequent radial forces in a welding arc column

3.2. The Current Descriptive Model for Plasma Jet

The most accepted model to explain plasma jet formation was described by Lin and Eagar (1986) and through equations by Richardson (1989) in one of his class notes. In summary, as presented by Figure 5, this model considers that there is a distribution of pressure in the arc in radial and axial directions. According to the model, this distribution is caused by the magnetic force field, which is different along the arc due to its shape (caused by the difference in size of the poles). As the pressure is higher in regions close to the electrode than the pressure close to the plate, there is a flow of plasma from the electrode to the plate, the so called plasma jet.

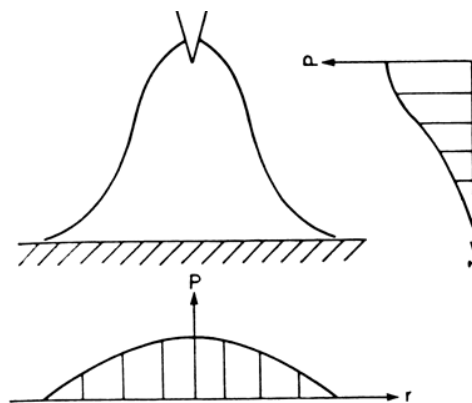


Figure 5: Pressure distribution along radial and axial directions according to Lin and Eagar (1986)

Even though the model explains the plasma jet phenomenon and it is widely accepted, two questions could emerge: a) if the pressure in the radial direction is higher in the centre than in the periphery of the arc, why does not plasma flow away from the arc towards this direction?; b) if plasma is a compressible matter, and the arc has no physical boundaries, how could electromagnetic forces push the bulk of the gas and plasma masses towards the centre line of the arc? A magnetic field would certainly not increase the pressure of a not confined amount of gas (not charged matter). Thus, at least a more comprehensive description of the phenomenon must be provided to prevent such questions.

3.3. The Proposed Descriptive Model for Plasma Jet

The authors of this work believe that the mentioned model for plasma jet formation is incomplete in terms of physical explanation and decided to suggest a model, aiming to improve the current understanding of the subject and looking for a point of common sense amongst welding users on the phenomenon (at least from the engineering point of view). In order to explain, in a more comprehensive approach, how the arc pressure distribution takes place, a model is proposed based in simple analogies as follows.

Consider a box filled with gas with a sliding wall connected to a shaft, as shown in the above part of Figure 6(a). If the sliding wall is pushed by a mechanical force from position 1 to position 2, the gas in the box will be under a pressure P_2 , which is higher than P_1 . This gas compression is commonly stated as thermodynamic pressure. On the other hand, if the same experiment is conducted without the sliding wall, that is, the same force is applied to the shaft only (Figure 6(b)), the pressure over the gas does not change (after reaching a statistic stead state), since there is no barrier to avoid the gas from exhausting. Thus, in the case of a gas (neutral particles), a volume of gas cannot be compressed if there are no barriers all around.

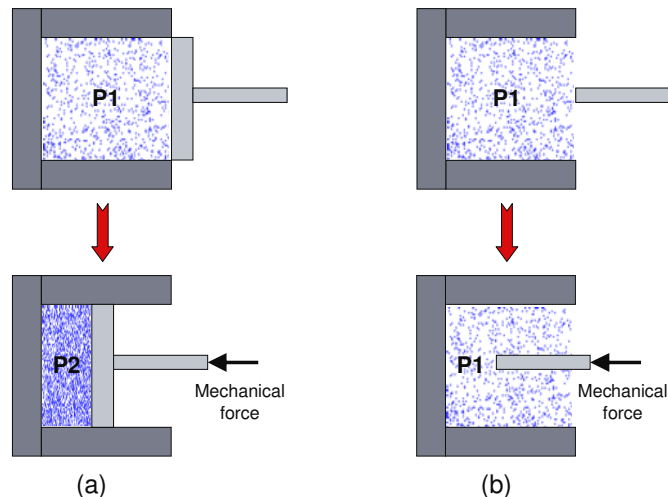


Figure 6: The thermodynamic pressure ($P_2 > P_1$) case

Now, let's replace the box by two horizontal walls charged (one positive and the other one negative), isolated from each other by a vertical neutral wall. If the gas is swapped by charged particles, these particles will tend to move from one pole to the other (Figure 7(a)). If this assembly is now put under a perpendicular magnetic field, as showed by Figure 7(b), a force will appear on each particle and they will be driven towards the vertical wall. Although there is not a physical barrier on the right side of the box (as in Figure 6(a)), these particles are similarly compressed (Figure 7(c)). The reason is that each single charged particle is driven towards the vertical wall by a force, preventing them from exhausting towards the right side, as happened in the case of Figure 6(b). Thus, in contrast to a mechanical force, a magnetic force is able to compress charged particles, even without a physical barrier

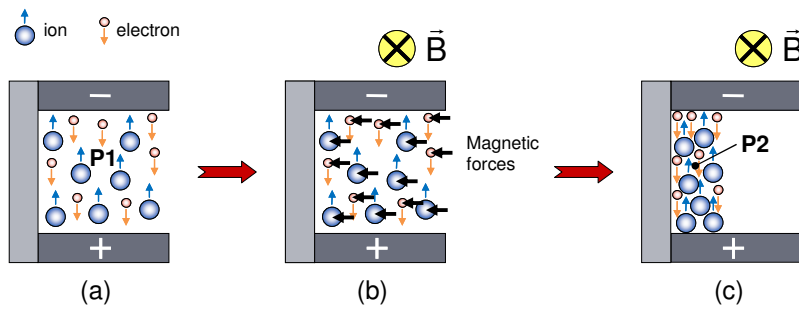


Figure 7: The case of the pressure due to magnetic forces ($P_2 > P_1$)

Figure 8(a), in turn, illustrates a situation in which two assemblies similar to the one in Figure 7(a) are put together, inverse side to side (note that the magnetic field orientation is different in each assembly). If the vertical walls are removed (Figure 8(b)), this new assembly is an analogy to a current-carrying conductor, which induces a circular magnetic field profile (entering from the right and exiting from the left). This, in fact, is a schematic model of a welding arc. Consequently, in a welding arc, charged particles would be compressed in a radial way towards the centre of the arc, increasing the density of charged particles, therefore, the pressure, from the arc periphery to the arc centre. Considering this fact as truth, the increase in the density of charged particles would also justify why the density of current is higher in the centre of the arc. As the magnetic forces on the charged particles, in totality, are similar to a barrier, there is no manner these particles can escape, even with a pressure higher in the centre than in the periphery of the arc. As the axial component of the magnetic force is low in the arc, there are no forces preventing the charges from moving in the arc column axis.

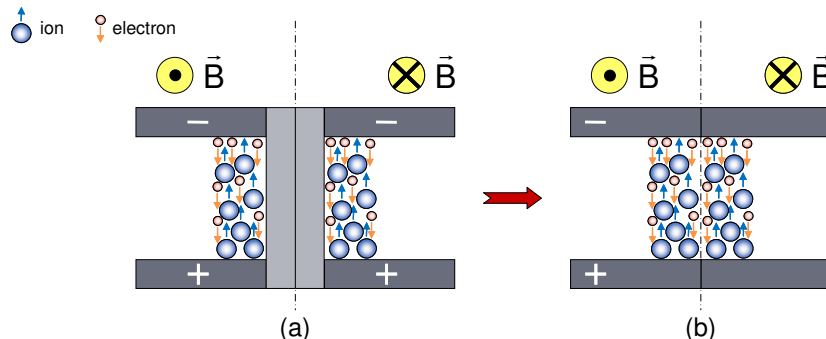


Figure 8: The schematic model of a welding arc showing compressed particles due to magnetic field, with no physical barrier

Now it is necessary to look for a reason for difference of pressure in the arc axial direction, which would justify the existence of matter movement (plasma jet). Considering that the electrical current is conducted through the entire arc (see Figure 9), yet not homogeneously, there is more current flowing through a section with a radius " R " in the position " a " than through the same section in the position " b ". Thus the magnetic field flux induced at point " A " would be more intense than the one induced at point " B ". Thus, the magnetic force on a particle situated at the point " A " would be stronger than on a particle situated at the point " B ". As arc radii are shorter close to the electrode, the pressure is higher in this region than in the regions approximating to the plate, as illustrated in Figure 10. Thus, since the charged particles cannot escape in a radial way and there is a difference of pressure along the arc length (high close to the electrode and low close to the plate), a flow of plasma (mass movement) from the electrode to the plate is formed (plasma jet).

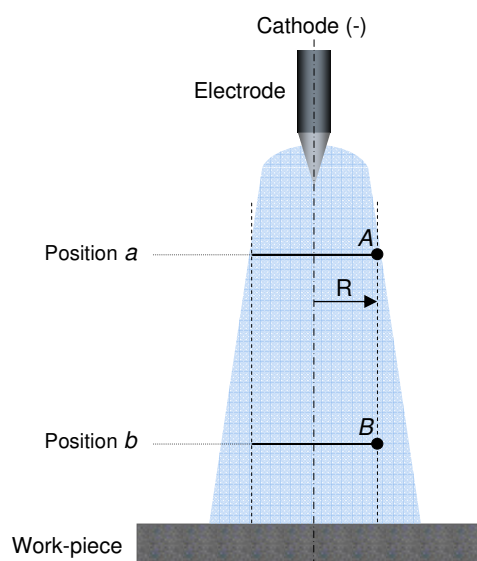


Figure 9: Two points at the same distance to the arc centre, but under uneven magnetic forces

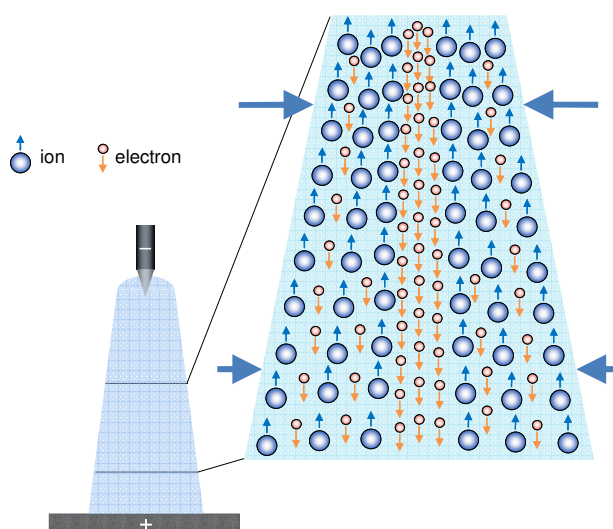


Figure 10: Charged particles compressed towards the arc centre line. The pressure is the highest closer to the electrode and progressively smaller on the way to the plate

Finally, it is mandatory to discuss the plasma jet composition. Electrons have no significant mass and cannot be responsible for the transportation of matter. Ions, on the contrary, could be. However, electrons and ions have a defined path, which is ruled according to the pole configuration. If the electrode is at the negative pole, ions must flow from the plate to the electrode, in the opposite direction of the plasma jet. This fact indicates the plasma jet is not formed exactly by movement of ions; otherwise plasma jet would occur only with the electrode at the positive polarity. The authors imply there might be two hypotheses for mass transportation, one not excluding the other. In the first one, the mass of ions can be transported from the electrode to the plate (plasma jet direction), whatever the electrode polarity, because the charge of the ions do not move with the mass. In a simplistic way of conceiving this phenomenon, it is like having the mass of ions moving to one direction, but the charges jumping, one after the other, to the next ion. Then, it is possible to have charges and masses travelling in opposite direction. In the second hypothesis, the mass of ions arrests or pulls (drags) non-ionized matter, since the ions themselves have volume (to compress atoms between them) and high speed (aerodynamic effect).

Summarizing, according to the proposed descriptive model, plasma jet (high speed movement of mass usually from the electrode to the plate surface) would be produced by a gradient of pressure along the arc axial direction. The pressure is caused by radial magnetic forces driven by a self-induced magnetic field around the arc column and perpendicular to the current flow. These forces push charged particles in the arc (mainly ions, which has significant mass) towards the arc centre. The gradient of pressure happens because of the arc shape, with stronger forces where the arc diameter is smaller.

3.4. The Plasma Jet Role in the Welding Arc Direction

The trajectory of the electrical arc may be ruled basically by two factors; the plasma jet and the electrical charge flow (current). As plasma jet is produced as a function of the magnetic forces, which, in turn, is generated by the current passing through the conductor (welding arc), it is difficult to define which one is the responsible for the arc trajectory. In order to identify the role played by both factors in welding arc formation, some experiments were carried out using the GTAW process. Figure 11 shows very low current arcs obtained through a high-frequency igniter and shielded by a low flow of Argon. In this case, the arc was driven by the shortest distance between the electrode and the plate. At the left side of Figure 11, the electrode was closer to the horizontal plate, whilst at the right side the electrode was placed closer to the vertical plate. As soon as the distance to the vertical plate becomes shorter than the distance to the horizontal plate, the arc changes its direction. This takes place due to the fact the electrons always look for the path with the lowest resistance, in this case, the shortest path. This indicates that in plasmas formed by low currents, the charge flow dictates the trajectory of the electrical arc, which could be called the electrons natural path effect.

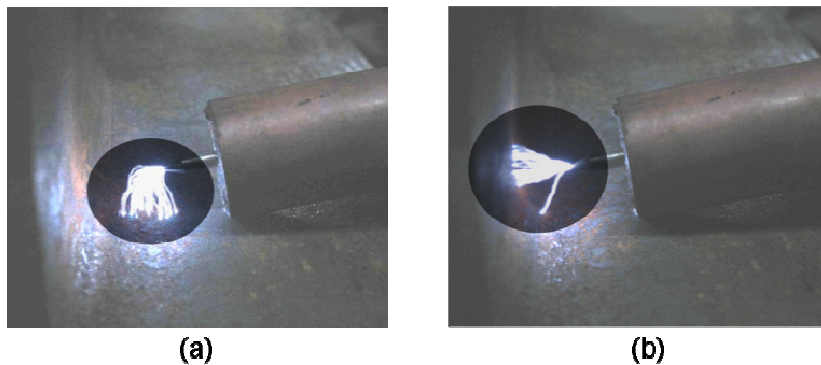


Figure 11: Very low current arcs obtained through a high-frequency igniter and low Argon flow in the inner corner of a steel angle bar: (a) electrode tip is closer to the horizontal side; (b) electrode tip is closer to the vertical side.

Figure 12 presents another arc formed by a low current produced by a high-frequency igniter and shielded by a low flow of Argon (electrode tip to plate distance was slightly longer than in Figure 11). It is worth noting the plasma shape has two regions with distinct orientations. The first one, close to the electrode, has the same direction of the electrode and the second one is perpendicular to the plate. This behaviour indicates that there are two factors influencing simultaneously; the mechanical effect of the plasma jet and the effect due to the electrons natural path.



Figure 12: Very low current arc obtained through a high-frequency igniter and low Argon flow showing the change in plasma orientation

One could expect that higher currents increase the plasma jet strength. Figure 13 shows now two actual GTAW arcs, with the same current level (100 A) and with vertical electrode to work-piece distances of 6 mm (a) and 12 mm (b). In the first picture (Figure 13(a)) it can be seen that for higher currents the region defined by the electrons natural path practically does not exist. This is probably due to the increase of the plasma jet influence, oriented to the electrode centre line. A 100 A current was enough to keep a plasma jet high intensity throughout the arc. However, as the arc length is increased (Figure 13(b)), it is possible to note a formation of a region in which the electrons natural path effect prevails. This probably takes place due to a loss of plasma jet intensity; plasma jet does not have enough intensity to keep the predominance through all the arc length.

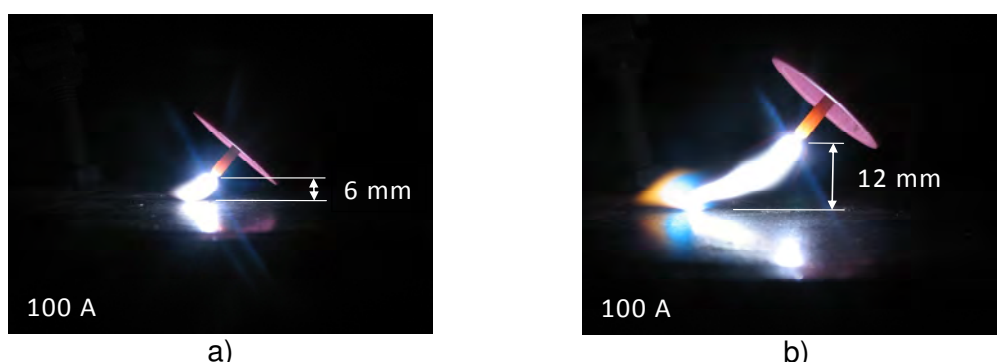


Figure 13: GTAW arcs with the same current level and different vertical electrode to work-piece distances: (a) the arc is short and plasma jet governs the arc trajectory; (b) the arc is longer and the electrons natural path effect overcome plasma jet effect at the end of the path

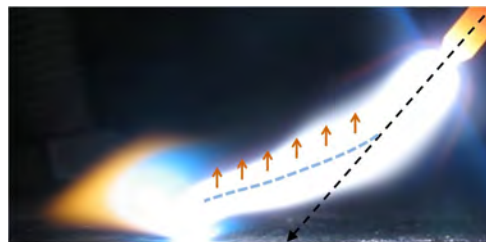
In order to improve visualization, both arcs showed in Figure 13 are presented again in Figure 14. By the thin dashed line drawn over the shorter arc (6 mm), it is evident the arc has the orientation of the electrode most of the time, which means the plasma jet effect is predominant. Taking now the 12-mm-long arc image, it is possible to observe the thick dashed line does not match all way long the line that has the same orientation of the electrode. It is supposed that up to a certain point the arc is mainly under the plasma jet influence (“region under the plasma jet effect”). Just before the arc reaches the plate it is suddenly deviated, changing to a vertical orientation and staying mainly under the electrons natural path influence (“region under the electrons natural path effect”). However, it is important verifying a third region with a distinct orientation. Arc trajectory in this third region may be, by hypothesis, related to two effects (Figure 15); the interaction between the plasma flow and the plate (fluid-dynamic effect) and the buoyant force effect, caused in the arc by the difference of density between arc and environs (thermal effect). This third region manifestation, which could be denominated “region under fluid-dynamic and/or thermal effect”, can now justify the large deviation of the 12-mm-long arc from the electrode centre line when the arc approaches the plate.



Figure 14: Regions under different effects in GTAW arcs with the same current level and different vertical electrode to work-piece distances



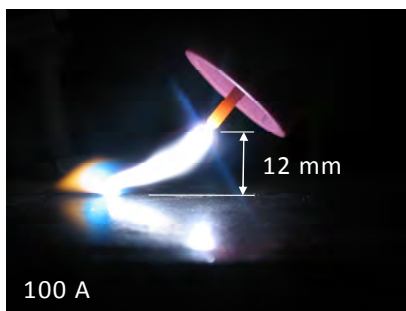
fluid-dynamic effect



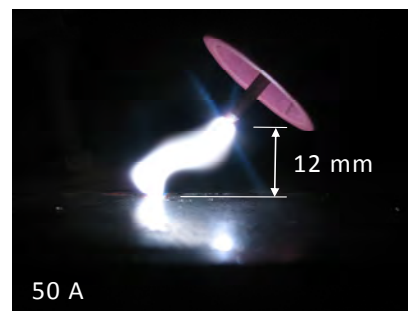
thermal effect

Figure 15: Fluid-dynamic effect (a) and thermal effect (b) on a welding arc trajectory

Figure 16 shows GTAW arcs with the same vertical electrode to work-piece distance, yet at different current levels. As the welding current is decreased from 100 to 50 A, keeping the same vertical electrode to work-piece distance (12 mm), it is possible to observe a variation in the extension of the regions; the region under the electrons natural path effect becomes more evident, while the regions under plasma jet and fluid-dynamic and/or thermal effects seem to weaken. This fact gives evidence of the fluid-dynamic effect, since a lower current level leads to a weaker plasma jet, consequently to a lower fluid speed.



a)



b)

Figure 16: GTAW arcs with the same vertical electrode to work-piece distance and different current levels

Another indication of the balance of effects that takes place to define the arc trajectory can be seen in Figure 17, which shows a GMAW in pulsed mode. When the current is at a low level (base current), plasma jet is not so strong and electrons natural path effect points the arc to the weld pool (shortest distance to achieve the plate). When the welding current is raised to a high level (peak current), the plasma jet effect gets stronger and points the arc straight down to the plate; the plasma jet effect prevails over the electrons natural path effect through all the arc length.

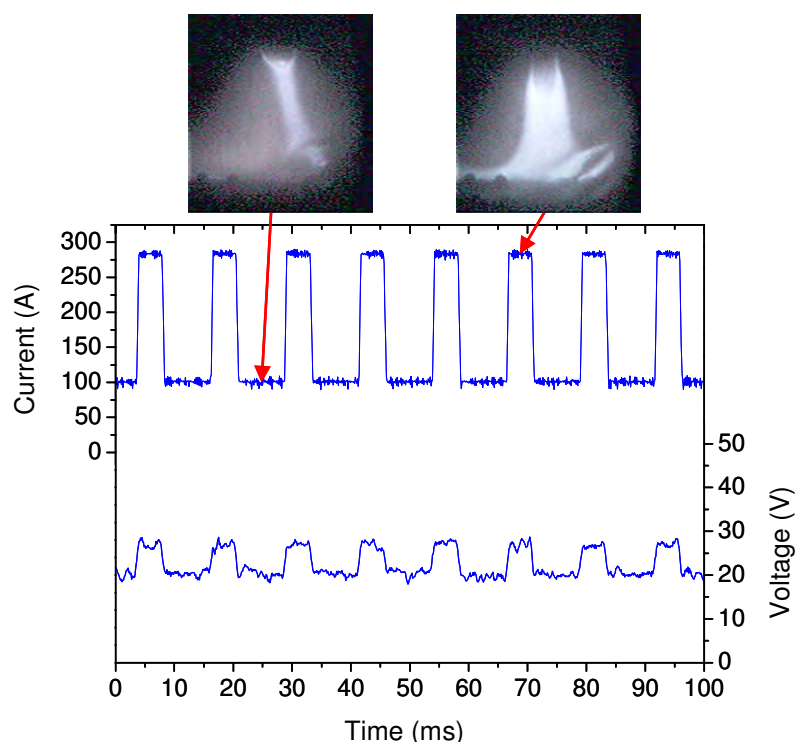


Figure 17: Welding current influence on the arc trajectory in pulsed GMA welding (After RESENDE, 2009)

4. The Arc Blow Phenomenon

4.1. General concepts

In normal conditions, the magnetic field induced by the electrical current conducted by the welding arc tends to be uniform around the arc column (the resultant magnetic force around the arc is null). However, at some circumstances, there may be an unbalance in the symmetry of the self induced magnetic field around the electrode, which produces a resultant force. This resultant force 'blows' the arc in a direction opposite to the concentration of magnetic flux density. The unwanted deflection or the wandering of a welding arc from its intended path is termed as arc blow. Currently, arc blow is widely spread as a problem in welding and it is related to porosity, weld bead irregularities, etc. Among the possible causes are the collimated and unidirectional current flow path (earth cable position), gradient of magnetic permeability between the material and the environment (edge effect and mass concentration), residual magnetic field and even external magnetic fields, as the one produced by another arc (tandem GMAW).

Despite the worldwide acceptance of the above mentioned explanation for arc blow, one question could be raised: Is it possible to have a plasma volume pushed aside due to unbalanced magnetic forces in such a way the arc column would change position? A magnetic field would certainly not move a not confined amount of gas (not charged matter). Thus, at least a more comprehensive description of the phenomenon must be provided to

avoid such questions.

4.2. The Proposed Descriptive Model for Arc Blow

Taking into account the resultant magnetic force interaction with the arc, two hypotheses can be considered:

- 1st - The arc (plasma column) moves and creates a new path for the electron flow;
- 2nd - The electron flow is displaced and forms a new path for the arc in another position.

The first hypothesis would be valid only if the resultant force responsible for the deflection of the plasma column had a thermodynamic nature. Only a thermodynamic pressure (like the atmospheric) would be able to push the arc (ionised and non-ionised matter) to another direction. In the precedent item, it was shown that magnetic field pushes charges, not non-ionized matter. On the other hand, the second hypothesis seems to represent what happens, since it is in accordance to the model proposed for the plasma jet formation. As illustrated in Figure 18, magnetic force acts on the charged particles only and these are the particles to be deviated. Once these charged particles (mainly electrons) go to another direction, they ionise a new path up to a point that the plasma column changes its direction.

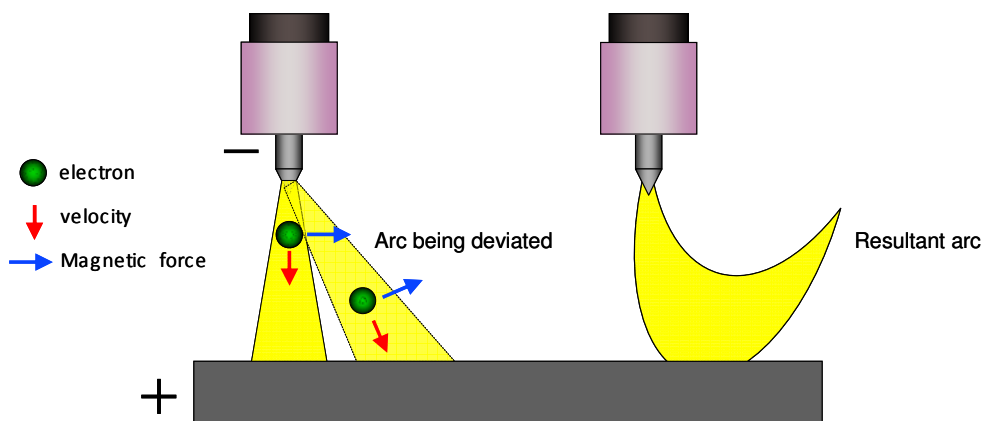


Figure 18: Welding arc being deviated as consequence of arc blow

5. Conclusions

The survey directed to a sample of researchers, professors, lectures and post-graduated students on welding technology, despite the lack of statistic significance, showed that there is some divergence in the description of plasma jet and arc blow formation phenomena.

Plasma jet formation would be better described as “the consequence of a gradient of pressure along the axial axis of an arc, pressure stronger close to the electrode (smaller area), which makes the plasmatic matter move at high speed towards the plate (larger area). The pressure, in turn, is created by an increasing density of charged particles towards the arc centre line, due to magnetic forces that push the charged particles radially inward, regardless the electrode polarity. The higher the current flow density (the closer to the electrode), the stronger the pressure”.

Plasma jet is not always the governing factor to define the arc trajectory. The influence of its effect becomes stronger as the current level is raised. However, there are two other factors playing concurrently, namely “fluid-dynamic and/or thermal effect” and “electrons natural path effect”. The “electrons natural path effect” becomes evident when the current is low. Concerning the “fluid-dynamic and/or thermal effect”, the dynamic part of the effect is

proportional to the “plasma jet effect”, that is, proportional to current level too.

Arc blow would be better described as “a deflection or a wandering of a welding arc from its intended path as a consequence of the displacement of its charged particles out of the way of the plasma column, in one direction, due to a force resulted from an unbalanced magnetic field around the arc (a new path for current flow is created away from the original one)”.

Finally, these presented models, yet endorsed by electromagnetic theory and by flow mechanics, still lack a deeper theoretical analysis (by physics) and experimental validations. So far, the authors claim they may be satisfactory under engineering point of view.

6. Acknowledgments

The authors wish to thank all team members of the welding group Laprosolda (Centre for Research and Development of Welding Processes) at Federal University of Uberlândia, Brazil, for the infrastructural support and discussions. They also give thanks to the Brazilian organisms for research development, Fapemig (through project TEC 1763/06), for the financial support, and CNPq, for the scholarships.

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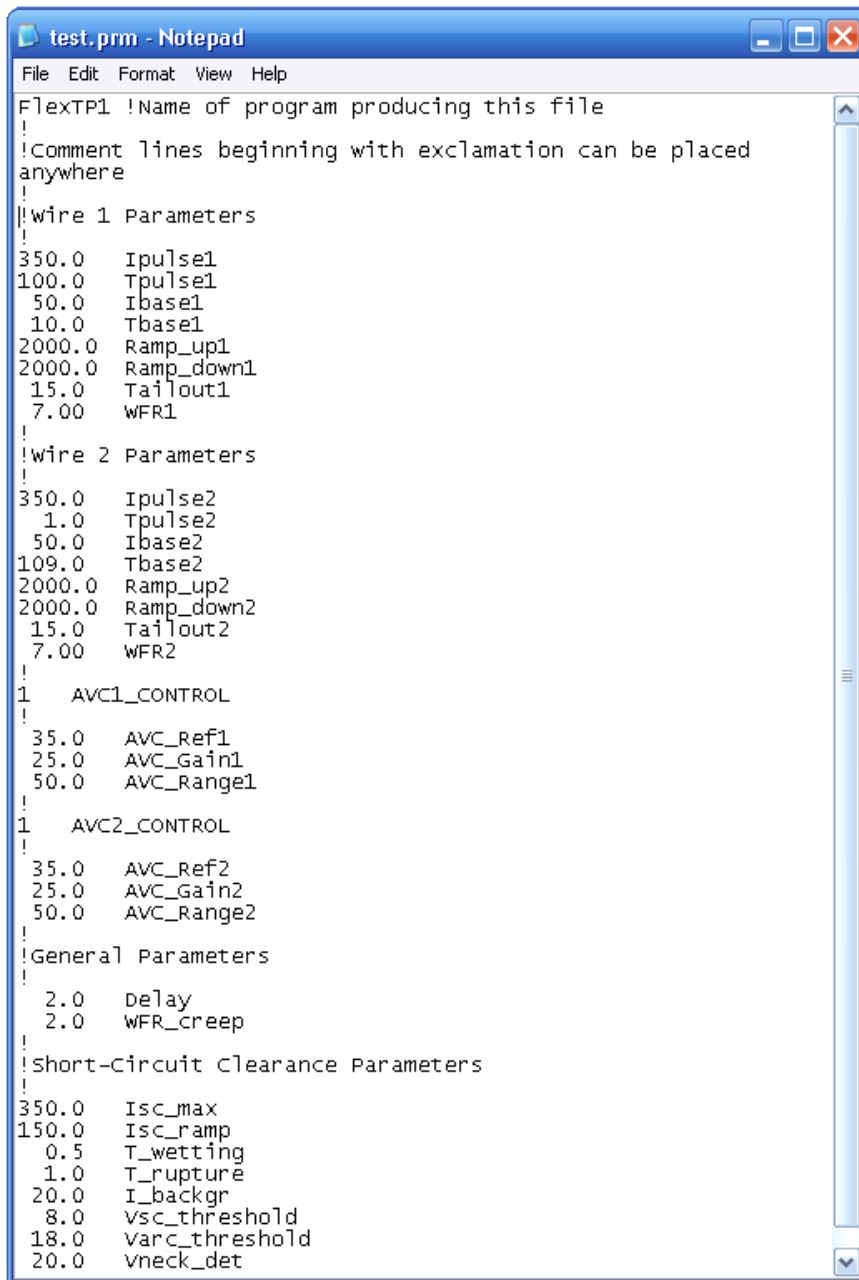
2 WELDING TRAVEL SPEED CALIBRATION

Table motion from Right to Left										
Run	Speed Control	Time measurement (s)			Travel Speed (mm/min)				Standard Deviation	
		Time 1	Time 2	Time 3	Average Time	Value 1	Value 2	Value 3		
1	15	206.12	195.27	188.97	196.79	87.33	92.18	95.25	91.59	3.996
2	20	101.70	100.89	97.43	100.01	176.99	178.41	184.75	180.05	4.130
3	25	67.47	66.38	66.24	66.70	266.79	271.17	271.74	269.90	2.710
4	30	49.99	50.19	48.96	49.71	360.07	358.64	367.65	362.12	4.841
5	35	40.76	40.38	39.87	40.34	441.61	445.77	451.47	446.28	4.949
6	40	33.97	33.45	33.31	33.58	529.88	538.12	540.38	536.12	5.526
7	45	28.82	28.68	28.63	28.71	624.57	627.62	628.71	626.96	2.148
8	50	25.51	25.28	25.42	25.40	705.61	712.03	708.10	708.58	3.236
9	55	22.50	22.54	22.29	22.44	800.00	798.58	807.54	802.04	4.814
10	60	20.28	20.11	19.96	20.12	887.57	895.08	901.80	894.82	7.118
11	65	18.47	18.19	18.15	18.27	974.55	989.55	991.74	985.28	9.354
12	70	16.89	16.77	16.58	16.75	1065.72	1073.35	1085.65	1074.90	10.054
13	75	15.43	15.49	15.43	15.45	1166.56	1162.04	1166.56	1165.05	2.609
14	80	14.43	14.23	14.28	14.31	1247.40	1264.93	1260.50	1257.61	9.117
15	85	13.37	13.22	13.27	13.29	1346.30	1361.57	1356.44	1354.77	7.774
16	90	12.48	12.53	12.43	12.48	1442.31	1436.55	1448.11	1442.32	5.779
17	95	11.80	11.67	11.74	11.74	1525.42	1542.42	1533.22	1533.69	8.506
18	100	11.12	11.06	11.03	11.07	1618.71	1627.49	1631.91	1626.03	6.723

Table motion from Left to Right										
Run	Speed Control	Time measurement (s)			Travel Speed (mm/min)				Standard Deviation	
		Time 1	Time 2	Time 3	Average Time	Value 1	Value 2	Value 3		
1	25	67.07	65.88	66.63	66.53	268.38	273.22	270.15	270.58	2.453
2	50	25.46	25.13	25.15	25.25	706.99	716.28	715.71	712.99	5.203
3	75	15.63	15.30	15.34	15.42	1151.63	1176.47	1173.40	1167.17	13.542
4	100	11.14	11.16	11.04	11.11	1615.80	1612.90	1630.43	1619.71	9.398

3 FLEXTANDEM - PULSED 1 PROGRAM FILES

Parameters file



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test.prm - Notepad
File Edit Format View Help
FlexTP1 !Name of program producing this file
!
!Comment lines beginning with exclamation can be placed
anywhere
!
!Wire 1 Parameters
!
350.0 Ipulse1
100.0 Tpulse1
50.0 Ibase1
10.0 Tbase1
2000.0 Ramp_up1
2000.0 Ramp_down1
15.0 Tailout1
7.00 WFR1
!
!Wire 2 Parameters
!
350.0 Ipulse2
1.0 Tpulse2
50.0 Ibase2
109.0 Tbase2
2000.0 Ramp_up2
2000.0 Ramp_down2
15.0 Tailout2
7.00 WFR2
!
1 AVC1_CONTROL
!
35.0 AVC_Ref1
25.0 AVC_Gain1
50.0 AVC_Range1
!
1 AVC2_CONTROL
!
35.0 AVC_Ref2
25.0 AVC_Gain2
50.0 AVC_Range2
!
!General Parameters
!
2.0 Delay
2.0 WFR_creep
!
!Short-Circuit Clearance Parameters
!
350.0 Isc_max
150.0 Isc_ramp
0.5 T_wetting
1.0 T_rupture
20.0 I_backgr
8.0 Vsc_threshold
18.0 Varc_threshold
20.0 vneck_det

```

Data logging file

```

Log.dat - Notepad
File Edit Format View Help

! DATA LOGGING FILE. Generated by FlexTP1 (PC GUI) & None (DSP program)

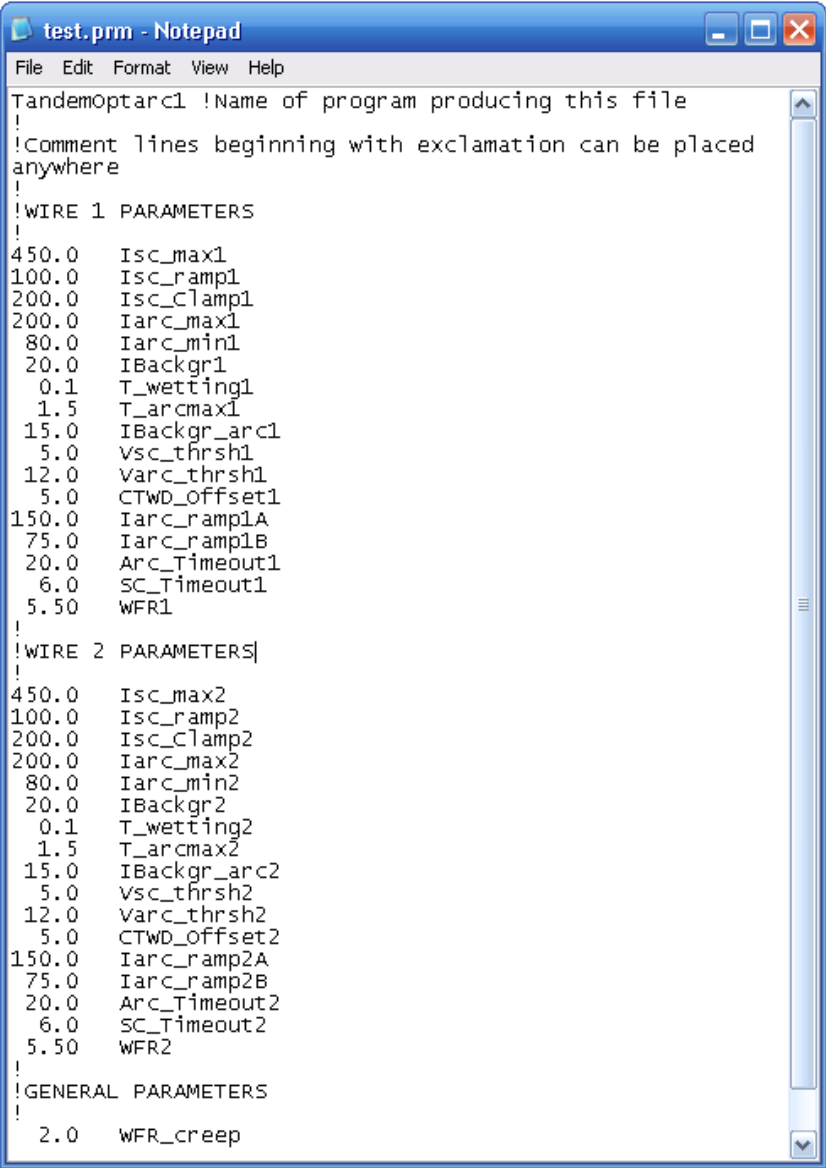
! WELDING PARAMETERS:
! Ipulse1: 350.0 A   Tpulse1: 100.0 ms   Ibase1: 50.0 A   Tbase1: 10.0 ms
! Ramp_up1: 2000.0 A/ms   Ramp_down1: 2000.0 A/ms   Tailout1: 15.0   WFR1: 7.00
m/min
! Ipulse2: 350.0 A   Tpulse2: 1.0 ms   Ibase2: 50.0 A   Tbase2: 109.0 ms
! Ramp_up2: 2000.0 A/ms   Ramp_down2: 2000.0 A/ms   Tailout2: 15.0   WFR2: 7.00
m/min
! Arc voltage Control 1
! ON
! AVC_Ref1: 35.0 V   AVC_Gain1: 25.0 A/V   AVC_Range1: 50.0 A
! Arc voltage Control 2
! ON
! AVC_Ref2: 35.0 V   AVC_Gain2: 25.0 A/V   AVC_Range2: 50.0 A
! General Parameters
! Delay: 2.0 ms   WFR_creep: 2.0 m/min
! Short_Circuit Clearance
! Isc_max: 350.0 A   Isc_ramp: 150.0 A/ms   T_wetting: 0.5 ms   T_rupture: 1.0 ms
! I_backgr: 20.0 A   Vsc_threshold: 8.0 V   Varc_threshold: 18.0 V   Vneck_det:
20.0 V
! SAMPLING:
! DSP sample time: 40.0 us   Log sampling time: 40.0 us
! No. of sample points: 1500   Total sampling time: 0.06 s

!
!   Time      Inst.      Inst.      Inst.      Inst.      vbase1      vbase2      variable
!   (ms)      Current1   voltage1   Current2   voltage2   average     average     8
!                                     (V)                                     ( )
!
!   0.00      250.00     22.50     250.00     22.50     20.00       20.00       8.00
!   0.04      250.01     22.51     250.01     22.51     20.01       20.01       8.01
!   0.08      250.02     22.52     250.02     22.52     20.02       20.02       8.02

```

4 TANDEMOPTARC - VERSION 1 PROGRAM FILES

Parameters file



```

test.prm - Notepad
File Edit Format View Help
TandemOptarc1 !Name of program producing this file
!Comment lines beginning with exclamation can be placed
anywhere
!WIRE 1 PARAMETERS
!
450.0   Isc_max1
100.0   Isc_ramp1
200.0   Isc_clamp1
200.0   Iarc_max1
80.0    Iarc_min1
20.0    IBackgr1
0.1     T_wetting1
1.5     T_arcmax1
15.0    IBackgr_arc1
5.0     Vsc_thrsh1
12.0    Varc_thrsh1
5.0     CTWD_offset1
150.0   Iarc_ramp1A
75.0    Iarc_ramp1B
20.0    Arc_Timeout1
6.0     SC_Timeout1
5.50    WFR1
!
!WIRE 2 PARAMETERS]
!
450.0   Isc_max2
100.0   Isc_ramp2
200.0   Isc_clamp2
200.0   Iarc_max2
80.0    Iarc_min2
20.0    IBackgr2
0.1     T_wetting2
1.5     T_arcmax2
15.0    IBackgr_arc2
5.0     Vsc_thrsh2
12.0    Varc_thrsh2
5.0     CTWD_offset2
150.0   Iarc_ramp2A
75.0    Iarc_ramp2B
20.0    Arc_Timeout2
6.0     SC_Timeout2
5.50    WFR2
!
!GENERAL PARAMETERS
!
2.0     WFR_creep
  
```

```

Log.dat - Notepad
File Edit Format View Help

|
|DATA LOGGING FILE
|Generated by Tandemoptarc1 (PC GUI) & None (DSP program)
|
|WELDING PARAMETERS
|
|WIRE 1
|
|Isc_max1: 450.0 A   Isc_ramp1: 100.0 A/ms   Iarc_max1: 200.0 A   Iarc_min1: 80.0 A
|IBackgr1: 20.0 A   T_wetting1: 0.1 ms   T_arcmax1: 1.5 ms   WFR1: 5.50 m/min
|IBackgr_arc1: 15.0 A   Vsc_thrsh1: 5.0 V   varc_thrsh1: 12.0 V
|!CTWD_Offset1: 5.0 mohms   Iarc_ramp1A: 150.0 A/ms   Iarc_ramp1B: 75.0 A/ms
|Arc_Timeout1: 20.0 ms   SC_Timeout1: 6.0 ms   Isc_Clamp1: 200.0 A
|
|WIRE 2
|
|Isc_max2: 450.0 A   Isc_ramp2: 100.0 A/ms   Iarc_max2: 200.0 A   Iarc_min2: 80.0 A
|IBackgr2: 20.0 A   T_wetting2: 0.1 ms   T_arcmax2: 1.5 ms   WFR2: 5.50 m/min
|IBackgr_arc2: 15.0 A   Vsc_thrsh2: 5.0 V   varc_thrsh2: 12.0 V
|!CTWD_Offset2: 5.0 mohms   Iarc_ramp2A: 150.0 A/ms   Iarc_ramp2B: 75.0 A/ms
|Arc_Timeout2: 20.0 ms   SC_Timeout2: 6.0 ms   Isc_Clamp2: 200.0 A
|
|GENERAL PARAMETERS
|
|WFR_creep: 2.0 m/min
|
|DSP sample time: 40.0 us   Log sampling time: 40.0 us
|No. of sample points: 1500   Total sampling time: 0.06 s
|
|Time      Inst.      Inst.      Inst.      Inst.      variable  variable  variable
| (ms)     Current1   voltage1   Current2   voltage2   ( )       ( )       ( )
|
|0.00      150.00      18.50      150.00      18.50      6.00      7.00      8.00
|0.04      150.01      18.51      150.01      18.51      6.01      7.01      8.01
|0.08      150.02      18.52      150.02      18.52      6.02      7.02      8.02
|

```

5 TANDEMOPTPULSE PROGRAM FILES

Parameters file



```

test - Notepad
File Edit Format View Help
;roptpulse1 'Name of program producing this file'
;
; Comment lines beginning with exclamation can be placed anywhere
;
; Wire 1 Parameters
450.0 Isc_max1
100.0 Isc_ramp1
200.0 Iarc_max1
80.0 Iarc_min1
20.0 IBackgr1
0.1 T_wetting1
1.5 T_arcmax1
15.0 IBackgr_arc1
200.0 Isc_clamp1
5.0 Vsc_thrsh1
12.0 Varc_thrsh1
150.0 Iarc_ramp1A
75.0 Iarc_ramp1B
20.0 Arc_Timeout1
6.0 SC_Timeout1
7.00 WFR1
;
; Wire 2 Parameters
350.0 Ipulse2
3.0 Tpulse2
50.0 Ibase2
14.0 Tbase2
2000.0 Ramp_up2
2000.0 Ramp_down2
1.0 Tailout2
7.00 WFR2
;
1 AVC2_CONTROL
;
18.0 AVC_Ref2
10.0 AVC_Gain2
30.0 AVC_Range2
;
; General Parameters
0.5 Delay
2.0 WFR_creep
;
; Short-Circuit Clearance Parameters - Wire 2
400.0 Isc_max
100.0 Isc_ramp
0.5 T_wetting
1.0 T_rupture
20.0 I_backgr
15.0 Vneck_det
5.0 Vsc_threshold
12.0 Varc_threshold

```

Data logging file

```
test - Notepad
File Edit Format View Help

DATA LOGGING FILE. Generated by Toptpulse1 (PC GUI) & None (DSP program)

WELDING PARAMETERS:
isc_max1: 450.0 A   isc_ramp1: 100.0 A/ms   iarc_max1: 200.0 A   iarc_min1: 80.0 A
Ibackgr1: 20.0 A   T_wetting1: 0.1 ms   T_arcmax1: 1.5 ms   IBackgr_arc1: 15.0 A
isc_clamp1: 200.0 A   vsc_thrsh1: 5.0 V   varc_thrsh1: 12.0 V   Iarc_ramp1A: 150.0 A/ms
Iarc_ramp1B: 75.0 A/ms   Arc_Timeout1: 20.0   SC_Timeout1: 6.0   WFR1: 7.00 m/min

Ipulse2: 350.0 A   Tpulse2: 3.0 ms   Ibase2: 50.0 A   Ibase2: 14.0 ms
Ramp_up2: 2000.0 A/ms   Ramp_down2: 2000.0 A/ms   Tailout2: 1.0   WFR2: 7.00 m/min

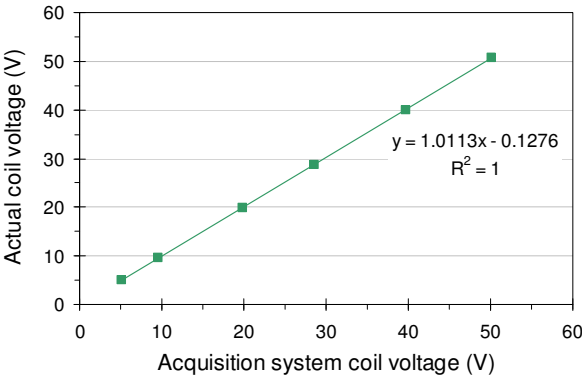
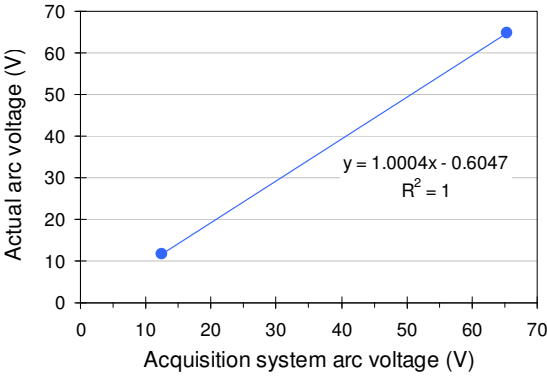
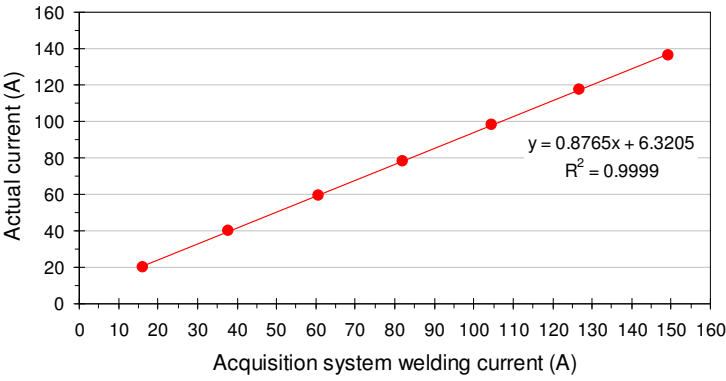
Arc Voltage Control 2
ON
AVC_Ref2: 18.0 V   AVC_Gain2: 10.0 A/V   AVC_Range2: 30.0 A

General Parameters
Delay: 0.5 ms   WFR_creep: 2.0 m/min
Short_Circuit Clearance - wire 2
isc_max: 400.0 A   isc_ramp: 100.0 A/ms   T_wetting: 0.5 ms   T_rupture: 1.0 ms
I_backgr: 20.0 A   vsc_threshold: 5.0 V   varc_threshold: 12.0 V   yneck_det: 15.0 V

SAMPLING:
DSP sample time: 40.0 us   Log sampling time: 40.0 us
No. of sample points: 1500   Total sampling time: 0.06 s

  Time    Inst.    Inst.    Inst.    Inst.    Variable    Variable    Variable
  (ms)    Current1 Voltage1 Current2 Voltage2      6          7          8
                (V)      (A)      (V)
0.00    250.00    22.50    250.00    22.50    20.00    20.00    8.00
0.04    250.01    22.51    250.01    22.51    20.01    20.01    8.01
0.08    250.02    22.52    250.02    22.52    20.02    20.02    8.02
```

6 CORRECTIONS FOR ACQUISITION SYSTEM USED IN CHAPTER 5



7 LAYOUT OF DC VOLTAGE SOURCE BUILT TO BE CONNECTED WITH THE ELECTROMAGNET

