

RUHAM PABLO REIS

ASSESSMENT OF LOW CURRENT TANDEM GMAW
PROCESSES WITH WAVEFORM CONTROL AND
WITH AID OF LASER BEAM



FEDERAL UNIVERSITY OF UBERLÂNDIA
FACULTY OF MECHANICAL ENGINEERING

2009

Ruham Pablo Reis

**ASSESSMENT OF LOW CURRENT TANDEM GMAW PROCESSES
WITH WAVEFORM CONTROL AND WITH AID OF LASER BEAM**

Thesis presented to the Post-Graduation Program in Mechanical Engineering of the Federal University of Uberlândia as part of the requisites to obtain the title of **DOCTOR IN MECHANICAL ENGINEERING**.

Concentration Area: Materials and Manufacturing Processes.

Supervisor: Prof. Dr. Américo Scotti

Co-supervisor: Prof. MSc. John Norrish

Dr. Dominic Cuiuri

UBERLÂNDIA - MG

2009

Dados Internacionais de Catalogação na Publicação (CIP)

- R375a Reis, Ruham Pablo, 1979-
 Assessment of low current tandem GMAW processes with waveform
 control and with aid of Laser beam / Ruham Pablo Reis. - 2009.
 290 p. : il.
- Orientador: Américo Scotti.
 Co-orientadores: John Norrish e Dominic Cuiuri.
- Tese (Doutorado) – Universidade Federal de Uberlândia, Programa
 de Pós-Graduação em Engenharia Mecânica.
 Inclui bibliografia.
1. Soldagem - Teses. I. Scotti, Américo, 1955- II. Norrish, John. III.
 Cuiuri, Dominic. IV. Universidade Federal de Uberlândia. Programa de
 Pós-Graduação em Engenharia Mecânica. V. Título.

CDU: 621.791



UNIVERSIDADE FEDERAL DE UBERLÂNDIA
FACULDADE DE ENGENHARIA MECÂNICA
PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA MECÂNICA
Av. João Naves de Ávila, 2121 - 38400-902 Fone: 0XX(34)32394149 Ramal 42
FAX: 0XX(34)32394282 – Campus Santa Mônica - Uberlândia MG



ALUNO: Ruham Pablo Reis

NÚMERO DE MATRÍCULA: 5052923

ÁREA DE CONCENTRAÇÃO: Materiais e Processos de Fabricação

PÓS-GRADUAÇÃO EM ENGENHARIA MECÂNICA: NÍVEL DOUTORADO

TÍTULO DA TESE:

“Assessment of Low Current Tandem GMAW Processes with Waveform Control and with Aid of Laser Beam”

ORIENTADOR: Prof. Dr. Américo Scotti

A Tese foi **APROVADA** em reunião pública, realizada na Sala 206 do Bloco 1M, Campus Santa Mônica, em 13 de novembro de 2009, às 14:00 horas, com a seguinte Banca Examinadora:

NOME	ASSINATURA
Prof. Dr. Américo Scotti	UFU _____
Prof. Dr. Volodymyr Ponomarov	UFU _____
Prof. Dr. Louriel Oliveira Vilarinho	UFU _____
Prof. Dr. Jair Carlos Dutra	UFSC _____
Prof. Dr. Hélio Cordeiro de Miranda	UFC _____
Prof. Dr. Willian Lucas (avaliador externo não presencial)	TWI(UK) _____

Uberlândia, 13 de novembro de 2009.

ACKNOWLEDGEMENTS

First of all I would like to express my sincere gratitude to my supervisors Prof. Américo Scotti, at Federal University of Uberlândia, and Prof. John Norrish and Dr. Dominic Cuiuri, at University of Wollongong, for providing me with many helpful suggestions, important advices and constant encouragement during the course of this work.

Sincere thanks are extended to Prof. Valtair Antonio Ferraresi, Prof. Louriel Oliveira Vilarinho, Prof. Volodymyr Ponomarov, Prof. Eduardo Kojy Takahashi and Prof. Ricardo Hernandez Pereira, for the ideas and advices, and to Alex Nicholson, Joe Abbott, Greg Tillman, Thiago Larquer and Lázaro Henrique, for devoting their time in helping me with laboratorial issues.

I also wish to express my appreciation to Daniel Souza and all colleagues at Federal University of Uberlândia, who made many valuable suggestions and gave constructive collaborations.

I would also like to thank the CNPq, for the award of scholarships during the time spent in Brazil and Australia for the development of this work, and the FAPEMIG, for the infrastructural support through the project TEC 1763/06.

I am also indebted to all staff of the Faculties of Mechanical Engineering at Federal University of Uberlândia and at University of Wollongong.

Special gratitude goes to Helen Newbold, Scott Pavy and Alex Newbold, for being my Australian family, and to all my Aussie friends, who made Australia feel like home.

I cannot end without thanking my family, on whose constant encouragement and love I have relied throughout my life. Their unflinching example will always inspire me. It is to them that I dedicate this work.

Ruham Pablo Reis

INDEX

<i>List of Symbols</i>	xi
<i>Abstract</i>	xiii
 CHAPTER I	
Introduction	1
 CHAPTER II	
Bibliographic Review	5
2.1 Controlled Short Circuit Transfer	5
2.2 Tandem GMAW	16
2.2.1 Tandem GMAW versus Twin GMAW	16
2.2.2 Pulsed GMAW	18
2.2.3 Tandem GMAW advantages and limitations	21
2.2.4 Parameters general influence	23
2.2.5 Difficulties in operating with pulsed mode in low mean current levels ..	24
2.3 Laser - GMAW Hybrid Welding	29
2.3.1 Laser Beam Welding	30
2.3.2 Type of Lasers used for welding	31
2.3.3 Laser - arc welding	32
2.3.4 Welding speed in Laser - arc hybrid welding	37
2.3.5 Gap tolerance (bridgeability) in Laser - arc welding	38
2.3.6 Reduction of porosity formation	40
2.3.7 Effects of hybrid welding parameters on the weld bead	42
2.3.8 New developments in Laser - arc hybrid welding	47
2.4 Magnetic Fields versus Welding Arcs	50

CHAPTER III

Equipments and Resources	55
3.1 Welding Table	55
3.1.1 <i>Travel speed calibration</i>	56
3.2 Tandem GMAW Torch	56
3.3 Backlight Sources and Data-Image Synchronisation and Analysis	59
3.3.1 <i>Backlight sources</i>	59
3.3.2 <i>Data-image synchronisation and analysis</i>	61
3.4 Extra Information	62
3.4.1 <i>Data acquisition</i>	62
3.4.2 <i>Power sources</i>	63
3.4.3 <i>Electrodes and gases</i>	63

CHAPTER IV

Study on Current Waveform Control	65
4.1 Tandem GMAW with Pulsed Current Waveform	65
4.1.1 <i>Controller</i>	65
4.1.2 <i>Description</i>	67
4.1.4 <i>General comments</i>	82
4.2 Pulsed Welding Condition with Low Mean Current	83
4.2.1 <i>Specimen and support used</i>	83
4.2.2 <i>Conditions for one droplet per pulse</i>	85
4.2.3 <i>Delay and plate surface condition effect</i>	92
4.2.4 <i>Inter-wire distance effect</i>	97
4.2.5 <i>General comments</i>	101
4.3 Tandem GMAW with Controlled Short-Circuit Waveform	102
4.3.1 <i>Introduction</i>	102
4.3.2 <i>Description</i>	103
4.3.3 <i>First trials using the TandemOptarc - Version 1 program</i>	110
4.3.4 <i>General comments</i>	112
4.4 Assessing the Tandem GMAW with Controlled Short-Circuit Mode	113
4.4.1 <i>Experimental conditions</i>	113
4.4.2 <i>Using the leading wire or the trailing wire in single configuration</i>	115
4.4.3 <i>Using wire 1 and wire 2 in tandem configuration</i>	121

4.4.4 General comments	129
4.5 Tandem GMAW with Controlled Short-Circuit and Pulsed Waveform	130
4.5.1 Introduction	130
4.5.2 Description	130
4.5.3 First trials using the TandemOptPulse1 program	135
4.5.4 General comments	152
CHAPTER V	
Study on Laser Beam Application	155
5.1 Introduction	155
5.2 Equipment Setup	155
5.3 First Evaluation of Laser - Tandem GMAW Process	160
5.3.1 Visual analysis of the process	163
5.3.2 Weld bead characteristics	182
5.4 General Comments	189
CHAPTER VI	
Study on the Effect of Magnetic Fields on Arc Stiffness	191
6.1 Characteristics of Magnetic Attraction between Welding Arcs	191
6.2 Electromagnet Design	195
6.3 Tests with GTAW Arcs	206
6.3.1 Welding current influence (arc deflected backwards)	211
6.3.2 Arc length influence (arc deflected backwards)	221
6.3.3 Torch angle influence (arc deflected backwards)	227
6.3.4 High-frequency current pulsing influence (arc deflected backwards) ...	231
6.3.5 Welding current influence (arc deflected forwards)	237
6.4 Considerations on the Arc Extinction Process	241
6.4.1 The case of tandem GMAW arcs	244
6.5 General Comments	248
CHAPTER VII	
Conclusions	249

CHAPTER VIII

Recommendations for Future Developments	253
--	------------

CHAPTER IX

Bibliographic References	257
---------------------------------------	------------

RESUMO EXTENDIDO (Extended Abstract)	265
---	------------

APPENDIXES	269
-------------------------	------------

1 Models to Describe Plasma Jet, Arc Trajectory and Arc Blow Formation in Arc Welding	269
2 Welding Travel Speed Calibration	282
3 FlexTandem - Pulsed 1 Program Files	283
4 TandemOptarc - Version 1 Program Files	285
5 TandemOptPulse Program Files	287
6 Corrections for the Acquisition System used in Chapter 5	289
7 Layout of DC Voltage Source built to be Connected with the Electromagnet ...	290

LIST OF SYMBOLS

AVC – Arc Voltage Control
CMT – Cold Metal Transfer
CTWD – Contact to Work-Piece Distance
DSP – Digital Signal Processor
GMA – Gas Metal Arc
GMAW – Gas Metal Arc Welding
GTAW – Gas Tungsten Arc Welding
HPDL – High Power Diode Lasers
HyDRA – Hybrid Welding with Double Rapid Arc
IPD – Inter-Pole Distance
IWD – Inter-Wire Distance
LBW – Laser Beam Welding
MFLOPS – Million Floating Point Operations per Second
PC – Personal Computer
RMD – Regulated Metal Deposition
STT – Surface Tension Transfer
WTS – Welding Travel Speed

REIS, R. P. **Assessment of Low Current Tandem GMAW Processes with Waveform Control and with Aid of Laser Beam.** 2009. 290 p. PhD Thesis, Federal University of Uberlândia, Uberlândia.

Abstract

In face of manufacturing-related limitations in the present-day industry, the welding sector has looked for new, or even not so new, processes. In other words, it has invested in the development of new processes and, especially, in the use of new arrangements for conventional processes. Thus, the aim of this work was to assess the use of combined processes and techniques as means of overcoming welding-related manufacturing limitations. In order to achieve this target, different tandem GMAW versions were assessed concerning welding current waveform control by developing dedicated softwares. The high-speed welding potential of a tandem process was coupled with the penetration control ability of controlled short-circuit and/or pulsed transfer modes. A combination of tandem GMAW with Laser beam welding was also assessed. As a consequence of difficulties faced in tandem GMAW, an investigation on arc interruptions was carried out by using electromagnetic fields to blow out the arcs. The tandem GMAW versions with both wires operating in controlled short-circuit mode and also with controlled short-circuit mode in the leading wire and pulsed mode in the trailing wire were highly unstable because of the intense interaction between the arcs and the weld pool. The tandem GMAW version with pulsed mode (low mean current) in both wires presented disturbances and interruptions, but such events were circumvented by using a very small delay between the current pulses of each wire. As the tandem pulsed GMAW was the only approach that showed practicability, it was combined with Laser beam welding. This hybrid process was able to increase the maximum welding travel speed or penetration depth significantly in comparison to tandem pulsed GMAW. The Laser beam showed to aid the tandem GMAW process, but more efficiently if placed half way between the wires. In relation to the investigation on arc interruptions, the higher the arc welding current and the shorter the arc length, the more the arc resists to the extinction. High-frequency current pulsing decreased the arc resistance to extinction. A model to explain the arc interruptions was proposed based on a heat balance in the arc column. Eventually, recommendations for future developments are presented.

Keywords: Tandem GMAW, Waveform Control, Laser-GMAW, Hybrid Welding, Arc Interruption.

CHAPTER I

INTRODUCTION

Driven by requirements for low cost, effective, fast and reliable production, the industrial need for sophisticated and advanced manufacturing solutions has increased. In face of this demand for productivity in the contemporary industry, the manufacturing sector has looked for new, or even not so new, processes. The goal has been to overcome manufacturing-related limitations of present-day processes. This is not different for welding and can only be achieved with comprehensible solution approaches. Therefore, solutions for welding-related manufacturing challenges have been accomplished by developing new processes and, especially, by using new arrangements for conventional processes.

A classical example of new approaches for welding is the use of hybrid processes in manufacturing plants. Laser beam added to GMAW has been reported to avoid welding defects at high welding travel speeds (CHO; FARSON, 2007, BAGGER; OLSEN, 2005). In this case, both energy sources act simultaneously in one welding zone, influencing and supporting each other. Others vanguard methods, also for highly productive welding, are tandem GMAW and waveform control for the welding current, which could be classified as combined and modified processes, respectively.

Let us, then, take an example on how a welding problem can lead to the use of an inovative manufacturing solution through hybrid welding. Müller and Koczera (2003) described a case in which it is shown how a German shipyard used a combination of Laser and GMAW to achieve one-sided welding. According to the authors, the new technology made significant productivity improvements. The one-side welding accomplished the goal of eliminating the need for heavy-plate panels to be flipped over. In addition, the minimal heat-induced distortion resulted in flat fabricated panels. No longer wavy and buckled, these panels did not require flattening. Furthermore, welding speeds changed to up to three times faster, compared to the GMAW the company was using before. As still claimed by these authors, thinner plates (up to 5 to 6 mm) could be welded at 2.5 to 3 m/min with the hybrid

process. Plates 15-mm thick could be welded at 1.2 m/min. The filler wire usage was also reduced by an estimated 80 percent. As seen, by using a hybrid approach, welding routines previously manually done, or at best with certain mechanical aids, such as tractors, could be performed without human intervention. This saves time and improves quality.

Let us now take the root runs case. Concerning pipeline constructions, welding is one of the most important issues. Assessing the case of pipeline welding as a whole, the root run is the first and more critical welding pass to be accomplish. This task is not so simple by itself and the difficulties are even increased as the weld metal must be deposited in overhead and vertical positions. A poor root run can deteriorate not only the deposition of subsequent weld runs (filling passes), but also introduce local discontinuities in the pipe inner surface, which can induce turbulent flows and erosion/corrosion, for instance. According to the American Petroleum Institute (API) 1004 specifications (HAHN, 2004), 80 to 90 percent of the pipe weld defects and inconsistencies are related to root runs. Therefore, a successful pipeline joint is almost synonymous of a successful root run.

In order to cope with the difficulties involved in root run welding, the GMAW process has been modified by using controlled waveforms for the welding current. This process enhancement method is in evidence in the equipments with controlled short-circuit transfer (STT, CMT, RMD, etc.), which have been designed to provide better control over the metal transfer and stabilisation of the heat input. These features, respectively, lead to spattering minimisation and allow sheet and root run welding. The techniques involving current waveform control have been industrially applied most frequently in manual (the so-called semi-automatic) approaches, with the claim of outstanding results in pipeline welding. However, there is the requirement for highly skilled welders. In addition, the pace of a pipeline is determined based on how fast the root run can be carried out (the longer the more expensive). Although some time can be saved by putting more than one welder for carrying out the job, there is a practical limit to this approach (two welders at most).

Considering the sensible improvements that have been carried out for the filling runs (YAPP; BLACKMAN, 2003), the productivity in pipeline construction has been each time more limited by the root run production. Thus, one option for pipeline welding would be the mechanisation of the root run. It would lead to higher metal deposition rates and, consequently, higher welding travel speeds than those developed by a human being, which means more productivity. However, it is still difficult to mimic the role played by the welder skill in the process. This shows that there is still challenges to be overcome and opportunities for innovative solutions in welding.

Back to the means of improving productivity in welding, perhaps the most promising way is by employing tandem GMAW. It has been a consensus that with this welding process

it is possible, at least, to double the welding travel speed and have penetration control with the pulsed transfer mode (OHNAWA et al., 2003, UHEYAMA et al., 2004). So a question emerges: why not try to join the virtues of two variants of GMAW? Such as by joining the stability and transfer control qualities of a controlled short-circuit and/or pulsed transfer mode to the high-speed welding potential of a tandem process. Furthermore, why not enhance the performance of such approach by means of a Laser beam? Unfortunately, when two processes are combined, not only the advantages might be joined, but also the limitations. For instance, by combining tandem GMAW with Laser beam welding, both regarded as high energy processes, burn-through problems are likely to take place. Moreover, there are still some intrinsic problems in such processes. Arc interruptions in tandem pulsed GMAW, for example, have been reported by Ueyama et al. (2005) when operating at low levels of mean current. In this case, despite some investigation, the cause of the respective problem is not well understood.

As seen, all the processes and techniques pointed out above present foreseen possibilities to be explored and exploited. As mentioned before, development must be coupled with comprehensible solution approaches; there is the need to understand phenomena involved in such cases. Thus, the aim of this work is to assess the use of combined processes and techniques as means of overcoming welding-related manufacturing limitations of the contemporary industry. In order to achieve this target, different versions of tandem GMAW, concerning welding current waveform control, are going to be assessed. The idea is to join the high-speed welding potential of a tandem process to the penetration control ability of controlled short-circuit and/or pulsed transfer modes. In addition, a combination of tandem GMAW with Laser beam welding, forming a highly productive hybrid process, is another possibility to be tried. As a consequence of difficulties faced in tandem GMAW, an specific objective of this work is to investigate arc instabilities and interruptions.

Figure 1.1 summarizes the structure of the research to be carried out. It is worth mentioning that this work has an exploratory approach and essentially it tries to point out alternatives for mechanised welding that might be applied to a range of cases.

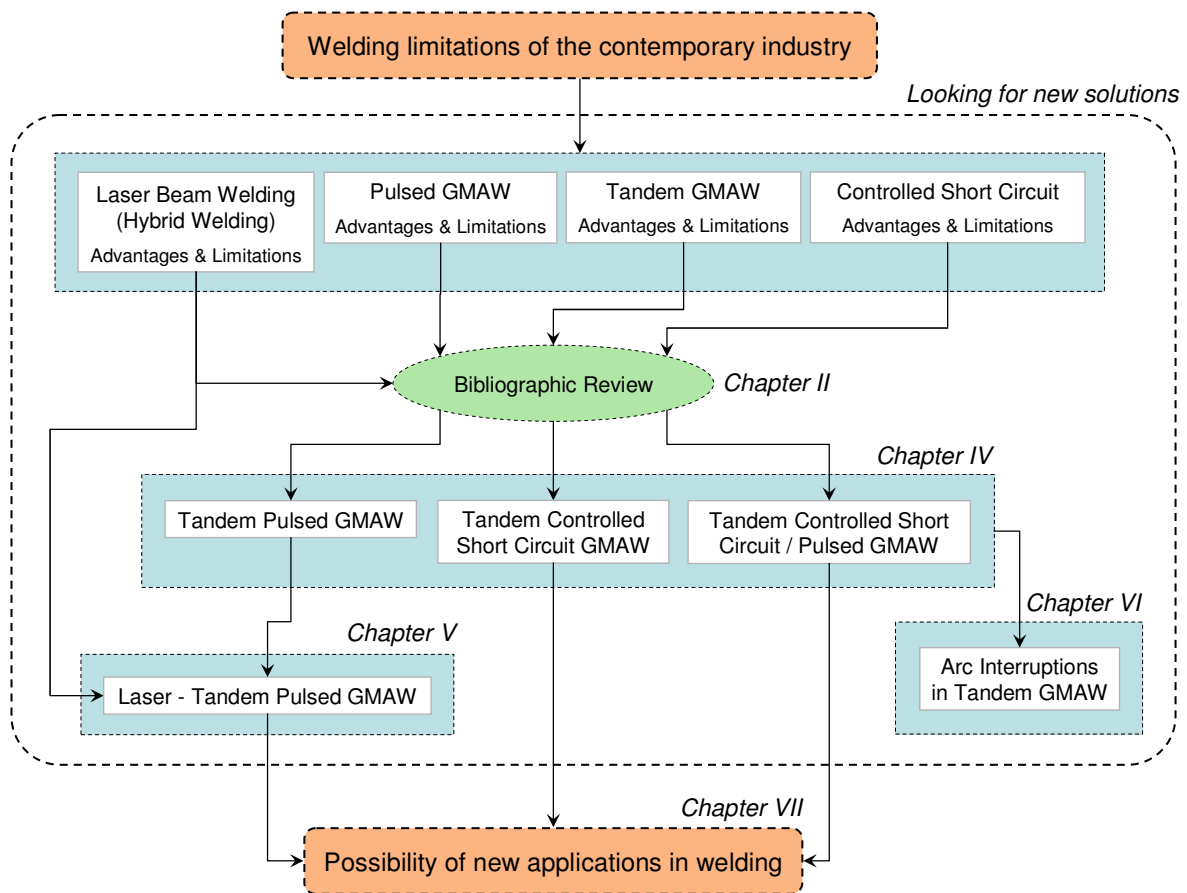


Figure 1.1: Summarized structure of the research

CHAPTER II

BIBLIOGRAPHIC REVIEW

2.1 Controlled Short-circuit Transfer

Before introducing the controlled short-circuit transfer methods (based mainly in current waveforms), firstly it is useful to describe the “conventional” (uncontrolled) short-circuit transfer mode and the commonly used stability evaluation methods for this transfer mode.

In the short-circuit transfer (or dip transfer) mode all metal transfer occurs when the electrode is in contact with the molten weld pool on the workpiece. The power source characteristics (constant voltage) control the relationship between the intermittent establishment of an electrical arc and the short circuiting of the electrode to the workpiece, as shown in Figure 2.1. As the name means, the short-circuit transfer mode is defined by the contact between the droplet at the tip of the electrode and the weld pool. The droplet is driven into the weld pool by electromagnetic and surface tension forces and a liquid metal bridge is established. This metal bridge is strangulated by the continuous flow of metal and increased pinch effect until its rupture. The arc is re-established and the sequence begins all over again. This metal transfer mode is regarded as a low density energy mode, thus the heat input into the base metal is generally low. This characteristic allows the short-circuit transfer mode to be applied in thin gauge sections (like thin sheets and root runs, for instance) and in positional welding.

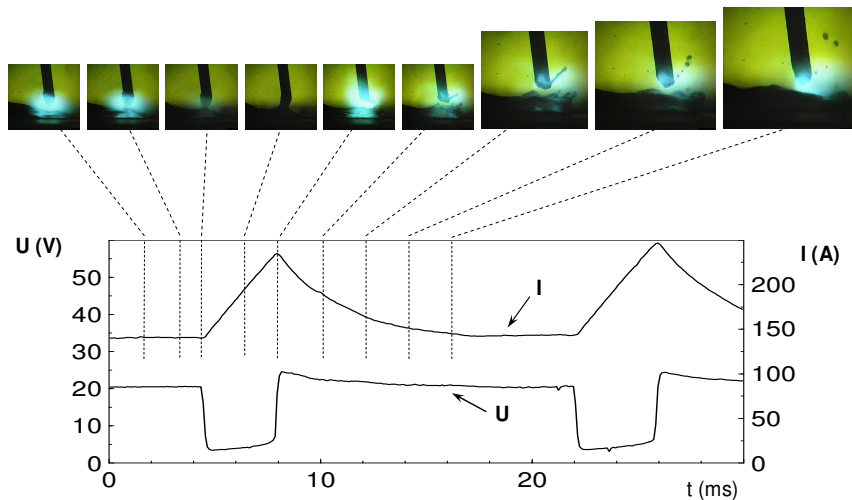


Figure 2.1: Example of electrical transient for current (I) and voltage (U) in short-circuit transfer mode and stages of the metal transfer

The most common means of short-circuit stability assessment is based on the electrical signals (current and voltage) analyses. An ideal arc (welding process totally stable) should have a uniform metal transfer, uniform arc burning and short-circuiting times (in short-circuit transfer case), the same time between the transfer of two consecutive drops (in spray transfer mode), the transfer of one droplet per pulse (in pulsed transfer case), a steady arc length and no spattering. Welding with a stable arc has a lot of advantages, such as economical (avoiding spattering less time is required to clean up the workpiece and torch nozzle) and operational (it is easier monitoring and controlling a stable process).

As the typical electrical signal of a short-circuit transfer can be divided in arc burning and short-circuiting phases along the time axis (Figure 2.2), this two times can be processed and presented in terms of probability distribution. By assessing the probability distribution of the short-circuiting phase, it is possible to determine if there is less or more variation in the time of this phase, therefore if the process is more or less stable. Figure 2.3 shows two probability distributions for two different shielding gases used in short-circuit GMA welding under the same welding parameters. According to Suban and Tusek (2003), the welding process is more stable for CO_2 as shielding gas, since the variation in the respective curve is smaller than in the Ar/CO_2 one. It is important to point out that when Suban and Tusek mentioned that CO_2 promotes more stable conditions, there is no evidence they tried to set the parameters for each case properly.

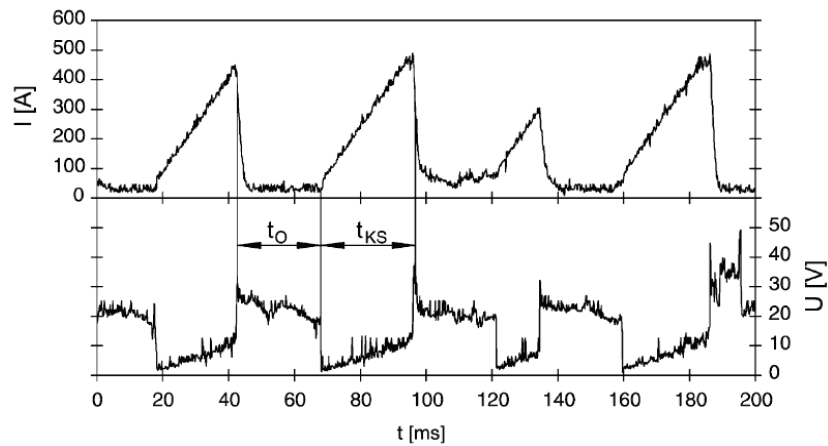


Figure 2.2: Arc burning (t_o) and short-circuiting (t_{KS}) phases in short-circuit electrical signals (SUBAN; TUSEK, 2003)

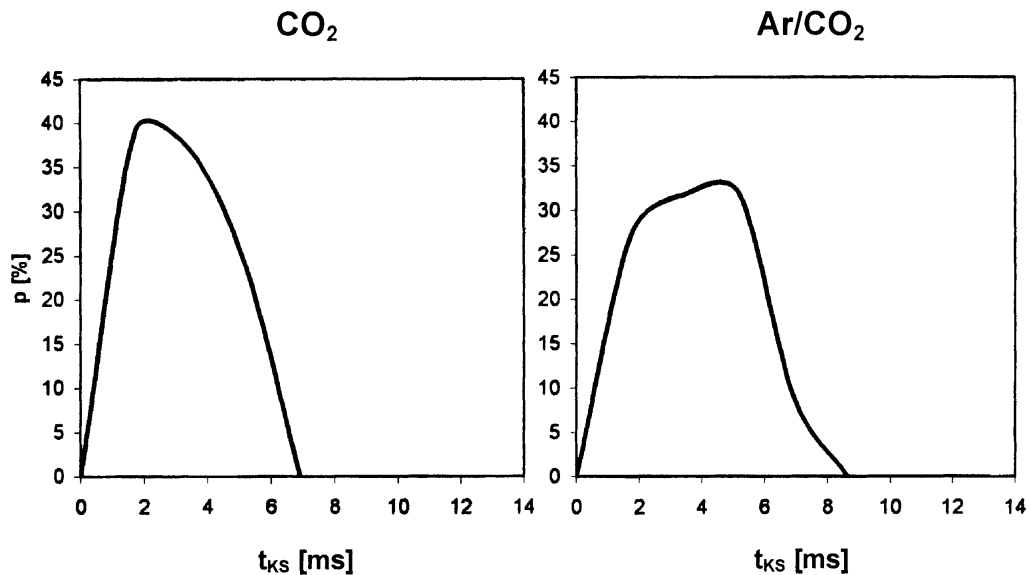


Figure 2.3: Probability distribution of short-circuiting phase with CO_2 and Ar/CO_2 as shielding gases (SUBAN; TUSEK, 2003)

Another way of analysing the stability in short-circuit transfer is by cyclogrammes, which present the arc voltage versus the welding current. Two zones in this graph may be noticed to analyse the stability. The arc period is defined by a high voltage and low current zone, and the short-circuiting period is defined by a low voltage and high current zone. Figure 2.4 presents cyclogrammes for the same welds performed in the Figure 2.3. The higher stability is found using the CO_2 gas, since the cyclogramme occupies a smaller area (the trace is neater). Fourier analyses can also be used as a stability assessment method. If the metal transfer is stable, the Fourier transformation will show a characteristic and main

remarkable frequency (SUBAN; TUSEK, 2003), otherwise more than one main characteristic frequency appears or it will be impossible to define the main frequencies.

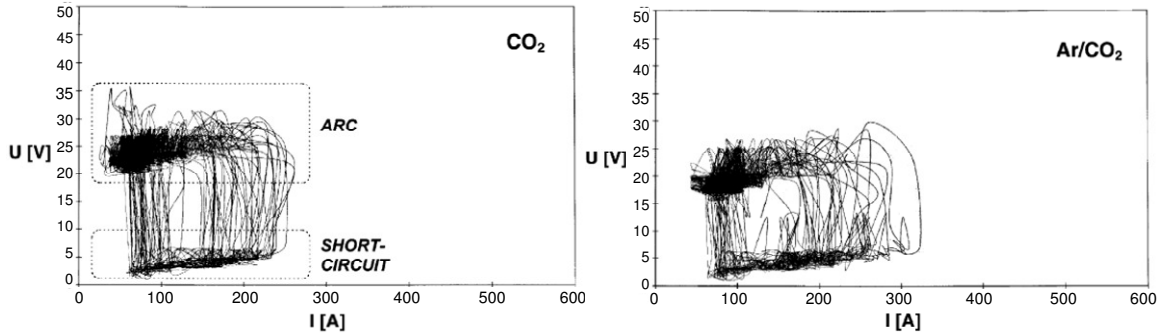


Figure 2.4: Cyclogrammes for short-circuit welding using CO₂ and Ar/CO₂ as shielding gases (SUBAN; TUSEK, 2003)

Another means of evaluating process stability in a short-circuit transfer, probably the most used, is by using stability indexes. For instance, the stability index (SI) can be defined as a function of the relation between the standard deviation of the weld cycle duration (σ) and the mean value of the weld cycle duration (T), as shown by Eq. (2.1) (CUIURI, 2000). This stability index is ranged from 0 to 1 and increases as the process regularity gets better. By using this method, values of stability index above 0.65 corresponded to good welds using the waveform control method showed in Figure 2.11 and values higher than 0.80 resulted in high quality welds for controlled short-circuit transfer (CUIURI, 2000).

$$SI = 1 - \frac{\sigma}{T} \quad (2.1)$$

The standard deviation of the short-circuiting frequency can be also taken as a stability index (HERMANS; DEN OUDEN, 1999). If the amount of short circuit is required to be evaluated, it is necessary to measure the mean duration of the short-circuiting period (t_c) and the mean period of the weld cycle (T). Thus, a short-circuit presence index (%SC) may be defined as shown by Eq. (2.2) (MODENESI; AVELAR, 1999).

$$\%SC = \frac{t_c}{T} \times 100 \quad (2.2)$$

In order to have enhancements (better stability, for instance) in the short-circuit transfer GMAW process, a lot of developments (BOUGHTON; MACGREGOR, 1974, OGASAWARA

et al., 1987, STAVA, 1993) have been tried and accomplished along the last 30 years dealing with current waveform control methods. The common and main objectives of all developments were the improvement of the metal transfer stability (absence of spattering) and better heat input control (penetration control). Almost all the previous and also the recent methods rely on the capability of rapid current turn off that is offered by modern power sources and in monitoring and feedback techniques to control the metallic transfer by an established waveform for the welding current. As a consequence of all these developments (methodologies, software and hardware), there are already some processes for controlled short-circuit transfer available in the market.

One of these techniques is the so-called STT™ (Surface Tension Transfer) (STAVA, 1993). This technique is a modified short-circuit GMAW process that claims to use high-frequency inverter technology with advanced waveform control to produce high quality welds while also significantly reducing spattering and fume generation. It has been advertised that the STT™ technology has the ability to control weld pool heat independently of wire feed speed. This fact enables more control over the weld pool and provides the ability to adjust the heat input to achieve the desired root bead profile (DERUNTZ, 2003). A description about how the STT™ process works is summarized as following (STAVA, 1993, DERUNTZ, 2003, LINCOLN ELECTRIC, 2007a).

Taking Figure 2.5 as a reference guide, in stage A a low level current (50 to 100 A), called background current, maintains the arc and controls the base metal heating. When the droplet at the tip of the electrode short-circuits with the weld pool, the current is quickly reduced to a very low level (10 A for 0.75 ms) (stage B) allowing the droplet to wet into the weld pool (at this stage the metal transfer is governed by surface tension action). After this wetting time, the stage C follows with a pinch current, which is responsible to push the molten metal (droplet) down into the weld pool (a pinch effect sums to the surface tension action to promote the metal transfer). Thus, as the short is about to break, the current is reduced to a low level again (around 50 A in microseconds) (stage D), but now to avoid the “explosion” of the liquid bridge and, therefore, the spatters. As soon as the arc is present (re-established) a peak current is applied (stage E). This current pulse sets the arc length by forcing the weld pool down and burning back the electrode in order to avoid an accidental short circuit. So the current returns to the background level through the tail-out control (rate that the current is changed from peak to background current level).

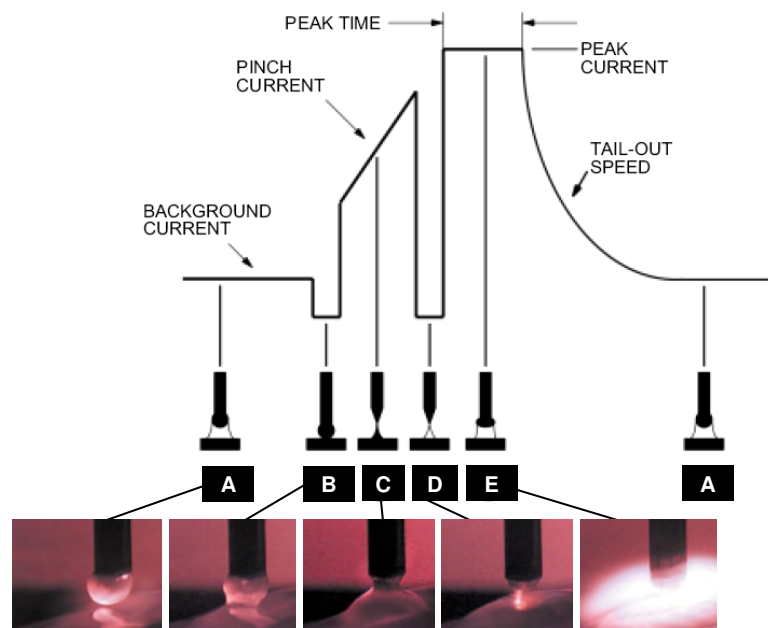


Figure 2.5: STT™ method waveform and metallic transfer stages (after LINCOLN ELECTRIC, 2007a)

The STT™ technique, as the name indicates, relies on the surface tension action to promote the metal transfer, but speeds up the metal transfer using a controlled pinch effect. The STT™ operating (setting) variables are wire feed speed, peak current, background current and tail-out. The wire feed speed controls the deposition rate. According to the STT™ manufacturer (LINCOLN ELECTRIC, 2007b), the peak current controls the arc length, which affects the shape of the weld root face (Figure 2.6), the background current is a “fine” heat control, which affects the back of the bead (Figure 2.7), and the tail-out setting serves as a “coarse” heat control (many open root applications set this control to zero). Figure 2.8 shows a typical weld bead on root run made using the STT™ process.

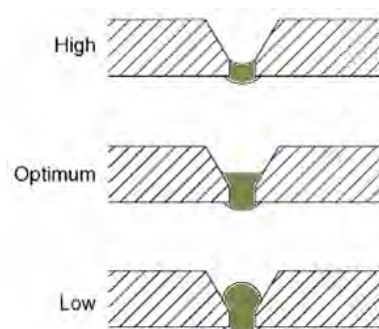


Figure 2.6: Effect of STT™ peak current on the root face (LINCOLN ELECTRIC, 2007b)

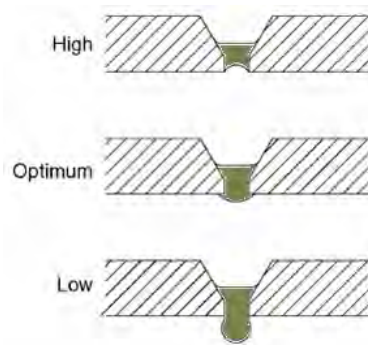


Figure 2.7: Effect of STT™ background current on the root back (LINCOLN ELECTRIC, 2007b)

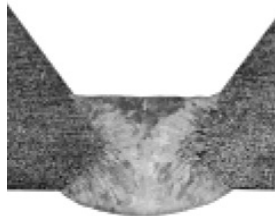


Figure 2.8: Typical weld bead on root run made using the STT™ process (LINCOLN ELECTRIC, 2007b)

Another commercial technique is the entitled RMD™ Pro (Regulated Metal Deposition). This technique is also a modified short-circuit GMAW process that precisely controls the electrode current during all phases of the droplet transfer. In other words, this technique also deals with current waveform control. It has been claimed that the RMD™ Pro lowers heat input by 5 to 20 % compared to a standard short-circuit transfer, minimizes spattering, provides a more stable weld pool, which facilitates for the welder to produce high quality root runs on pipes and accommodates poor fit-ups without difficulty (MILLER'S NEW, 2007). The RMD™ Pro process works as described in Figure 2.9. As it is possible to notice, the general waveform of the welding current is similar to the STT™ one. In stage A (wet stage) a droplet in the end of the electrode is given time to wet into the weld pool. After this time, in stage B (pinch stage) the current is sharply increased to a level high enough to promote a significant pinch effect. In stage C (clear stage) the pinch current is slightly increased to clear the short circuit. Upon pinch detection, in stage D (blink stage) the current rapidly decays to a low level before the short circuit breaks, allowing a smoother metal transfer. So in stage E the current is increased to form a droplet for the next short circuit (ball stage). Stage F (background stage) follows with the current decreasing to a level low enough to allow short circuiting. If this background current lasts for a relatively long time, stage G (pre-short stage) starts dropping

the current to an even lower level to allow the short circuit and to make sure the arc force does not push the weld pool back (prevents excessive agitation).

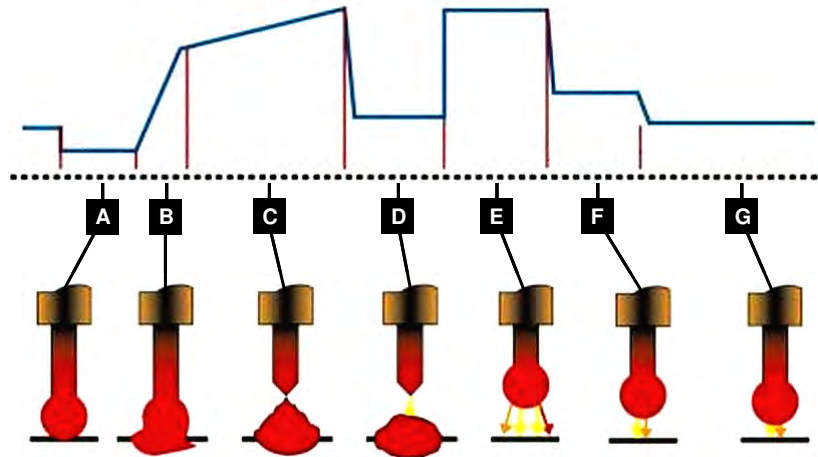


Figure 2.9: RMD™ method waveform and metallic transfer stages (after MILLER'S NEW, 2007)

Another available technique that relies on current waveform control to improve the short-circuit transfer GMAW process is the CMT™ (Cold Metal Transfer). But this technique manages also the movement of the wire (it feeds or returns the wire as necessary) to enhance the metal transfer dynamics. The CMT™ process works as described in Figure 2.10. In stage A, during the arcing period, the electrode is moved towards the weld pool. When the electrode short-circuits into the weld pool the arc is extinguished and stage B starts dropping the welding current to a low level. In stage C the short-circuit current is kept low and the rearward movement of the wire supports droplet detachment. Thus, in stage D the wire motion is reversed and the process cycle starts again. This method relies almost on the surface tension mechanism to promote the metallic transfer, except for the assistance from the wire returning movement.

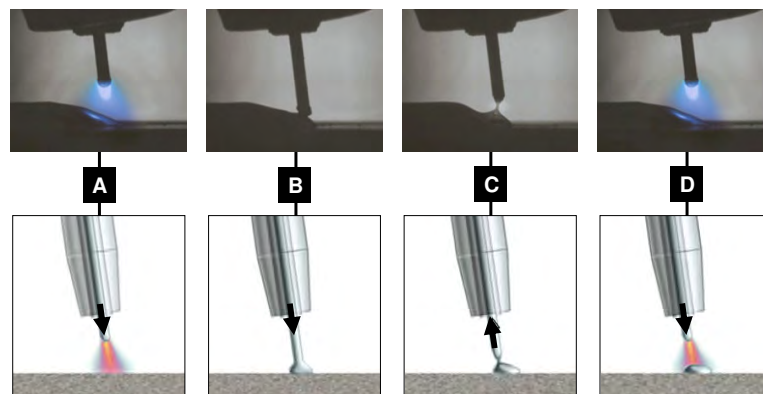


Figure 2.10: CMT™ metallic transfer stages (after CMT: COLD METAL TRANSFER, 2007)

Other techniques have been also developed in research centres around the world (CUIURI, 2000, DEAN, 2003, GONÇALVES e SILVA, 2005, CUIURI; NORRISH, 2006). Recently, researches at University of Wollongong, Australia, developed new approaches to control the short-circuit transfer. One of these approaches (CUIURI, 2000, CUIURI; NORRISH, 2006) also relies on the current rapid turn off capability of the power source. This method considers the welding cycle as a finite number of sequential steps (states), so that the output current can be controlled using different strategies (related to events or pre-determined time limits) depending on the weld state. The method uses two independent current controllers to supply the dynamic main current and the constant background current which is used as “pilot arc” (the welding current in each step is the sum of the main current and the background current).

This method for short-circuit transfer control is described in Figure 2.11. The beginning of a short-circuiting event (weld state 2) is detected by the controller as soon as the voltage drops below an established threshold V_{sc} (usually 5 V). Thus, the current is rapidly turned off and only the background current is allowed to flow through the welding circuit. Thus the droplet can wet into the weld pool for a specified time (the surface tension force is mainly acting). After this time, the current is sharply raised to 100 A at a high rate (300 A/ms) providing a significantly pinch effect to be applied to the liquid metal bridge. So a slower ramp (I_{sc_ramp}) is applied to the welding current until its value reaches the specified limit (I_{sc_max}). At stage 3 a premonition unit detects the onset of the short-circuit rupture and the main current is turned off (the weld state 3 extension is determined by the process behaviour). The current is maintained at the background value (weld state 4) to provide a smooth metal bridge rupture. In state 5 the arc is re-established and a high and fixed current (I_{arc_max}) is applied during a pre-determined time. This high current promotes a rapid electrode burn back and also pushes the weld pool down to provide a sufficient arc length avoiding an accidental short circuit. After the I_{arc_max} time, in weld state 6 the current is linearly dropped at a determined rate (I_{arc_ramp}) to an I_{arc_min} value. Thus the current is maintained at I_{arc_min} (weld state 1) to provide droplet growth and heat input to the work piece. The cycle re-starts when the droplet contacts the weld pool (short circuit). Regarding metal transfer, weld stability, amount of spatters and heat input control, this short-circuit transfer control method showed results similar to those achievable when using commercial approaches.

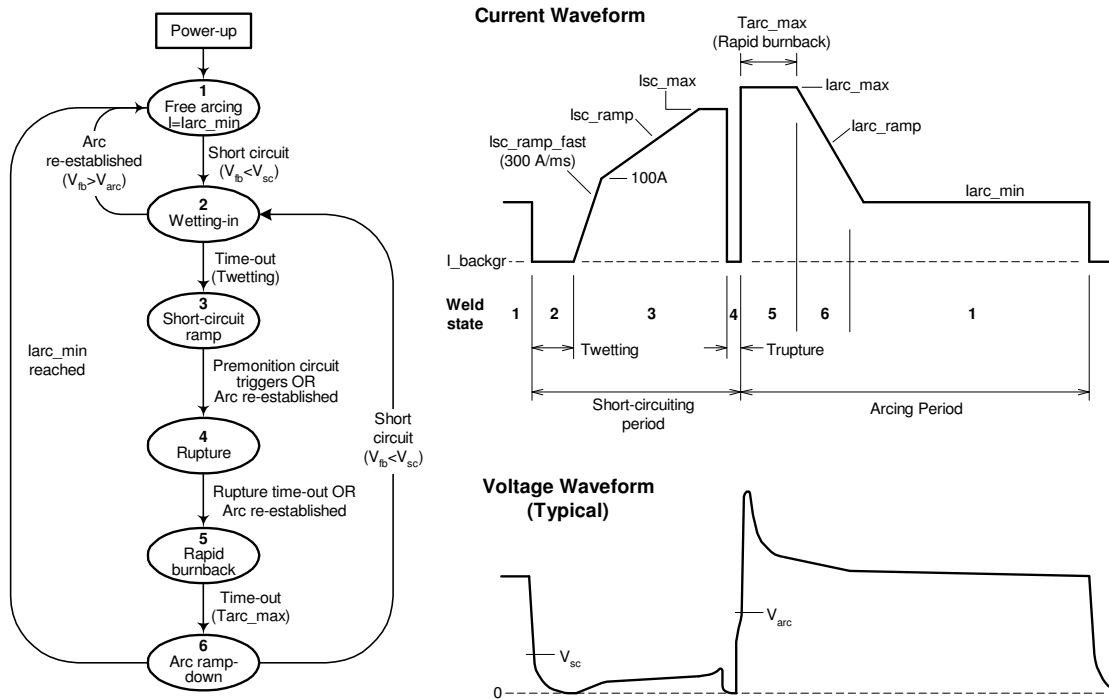


Figure 2.11: Logic diagram and typical waveform for controlled short-circuit transfer developed at UOW (CUIURI; NORRISH, 2006)

Another innovative technique (DEAN, 2003, CUIURI; NORRISH, 2006), also developed at University of Wollongong, tried a different approach to control the short-circuit transfer. This method relies practically in the surface tension force only to transfer the droplet to the weld pool and can be used with conventional inverter power sources, since it needs only the detection of the rapid voltage increasing on arc ignition and the rapid voltage decreasing at the beginning of the short circuit as references to control the process (it does not need the rapid current turn off capability neither the premonition detection for metal bridge rupture). This method was based on the principle that if a droplet has developed a critical size prior to short circuiting, surface tension forces can be used as the main droplet detachment mechanism. This alternative control technique uses a short-circuit current clamping methodology (the maximum short-circuit current is maintained at levels lower than those that normally would happen when using conventional constant voltage techniques). The advantage of using such methodology is that the short-circuit droplet transfer is allowed to occur predominantly under the influence of surface tension, since the pinch effect is limited by the low level of current applied. This method also minimizes spattering, since the short-circuit current is limited to low values, and it is able to control heat input (penetration control).

The waveform used by this control method is shown by Figure 2.12. Before the short circuit (weld state 1), the current level is that selected to provide workpiece heating. At the

short-circuit initiation, the current is reduced to allow the droplet a wetting-in time into the weld pool (weld state 2). After the wetting-in time, the short-circuit current is increased to the clamp level and held at this value until the metal bridge rupture (weld state 3). When the bridge rupture is detected, a current pulse is applied to push the weld pool down and promote the droplet growth, but without detachment (weld state 4). Then, the current returns to weld state 1, which controls the heat input, and the cycle starts all over again.

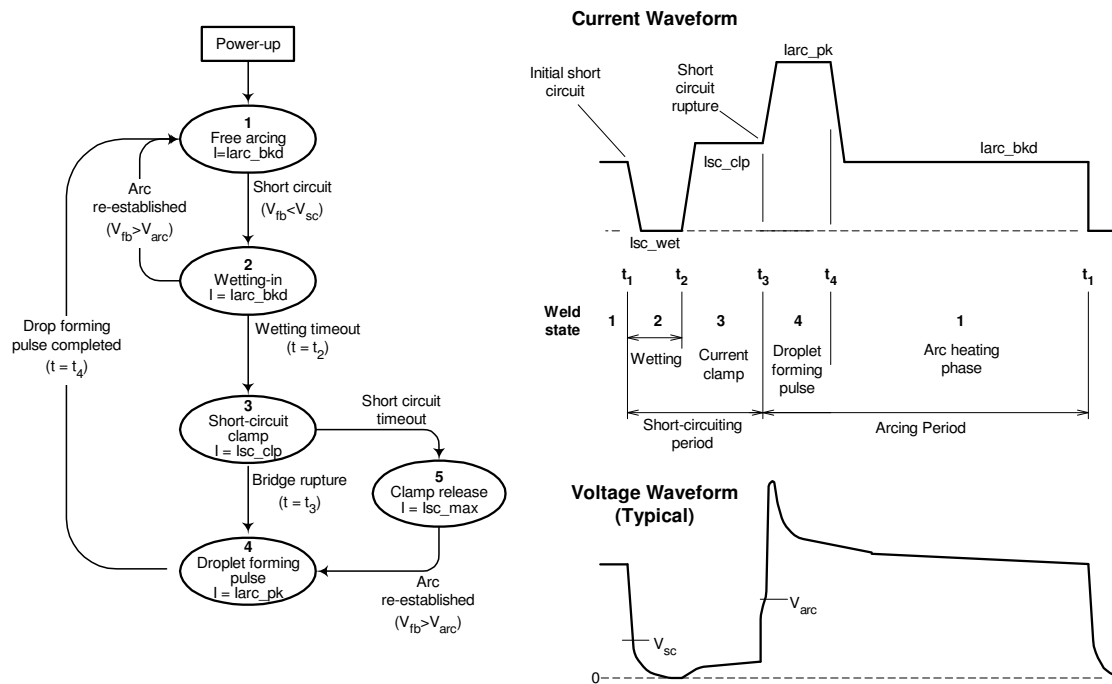


Figure 2.12: Logic diagram and typical waveform for another controlled short-circuit method developed at UOW (DEAN, 2003)

An earlier work indicated that controlled short-circuit transfer could be used to produce high integrity root runs using a mechanized approach (YAPP; BLACKMAN, 2003). This work showed that controlled short-circuit transfer allowed excellent control of penetration and no lack of fusion defects were found (Figure 2.13). Although the process operating envelope was found to be large (fusion defects appeared only if the welding torch was significantly displaced from the centreline of the weld), the typical travel speed reached was considered low (390 mm/min).

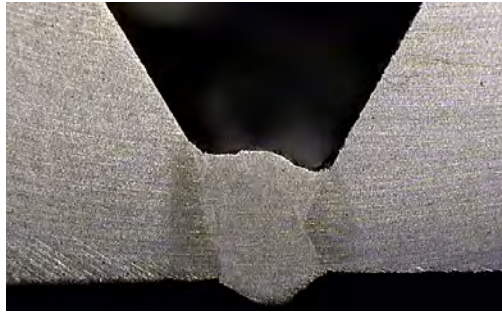


Figure 2.13: Root run performed using a controlled short-circuit process in a mechanized approach (YAPP; BLACKMAN, 2003)

2.2 Tandem GMAW

As a result of the continuous need for improvements in productivity (high welding travel speeds and/or high metal deposition rates) and due to the advanced power electronics available, new welding processes have been developed and some “reinvented” (reformulated for new applications) during the last years. One of these “new” processes is the Tandem/Twin GMAW. Ueyama et al. (2004) cite that the use of Tandem/Twin wires remote to the 1970's years, but only within the last decade the process became really feasible.

Previous to discussing further more about this process, it is important to define tandem GMAW, distinguish it from Twin GMAW and introduce the basis of pulsed GMAW (the usual transfer mode for tandem GMAW).

2.2.1 Tandem GMAW versus Twin GMAW

In general, a process is considered as tandem when two electrodes at separate electrical potentials feed into the same weld pool. With two electrically separate and insulated contact tips the arc length and, therefore, the metal transfer for each electrode wire can be individually regulated. Tandem GMA welding can be carried out by using a single torch (electrically isolated contact tips), as show schematically by Figure 2.14, or by using two separate torches (Figure 2.15). Most commercial systems employ a single torch design (more compact), since it facilitates joint access and mechanization/automation.

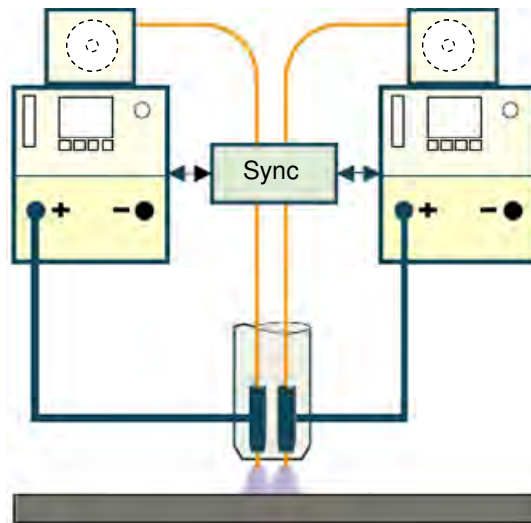


Figure 2.14: Typical system for tandem GMAW using a single torch

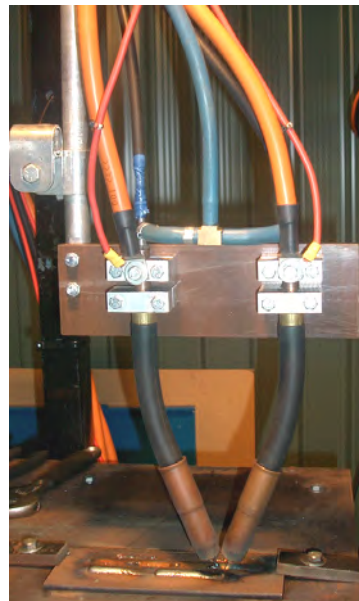


Figure 2.15: Experimental torch for tandem GMAW designed at University of Wollongong (CUIURI, 2000)

Generally, a process is regarded as twin when two electrodes at the same electrical potential feed into the same weld pool. The welding current is provided by one or two powers sources, and independent adjustments of the electrical parameters on each wire are not possible because the common potential design adopted as shown by Figure 2.16.

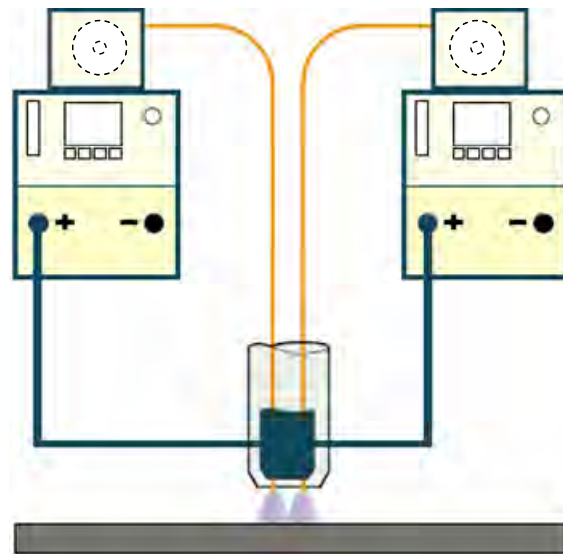


Figure 2.16: Typical system for twin GMAW

Although this general difference mentioned between the tandem and twin GMAW versions, in practical applications the use of such definitions are not a consensus. For this reason, in this work the tandem GMAW process will be considered as two GMAW wires connected to different electrical potentials (power sources) and feeding sequentially into the same weld pool.

2.2.2 Pulsed GMAW

The pulsed GMAW may be considered as the most popular application for waveform control in welding operations. It was developed to allow spray transfer mode at mean currents below the normal transition level of current (globular to spray transfer) for a given welding condition (NORRISH, 1992). In fact, pulsed GMAW is a modified spray transfer process. It can be considered that the pulsed GMAW tries to join the advantages of a spray transfer (process stability, good fusion, low spattering level, and beads with good visual appeal) to the advantages of a short-circuit transfer (low heat input and less prone to burn-through). In pulsed GMAW, a low background current is used to maintain the arc and the droplet detachment is provided by applying a high current pulse (high electromagnetic forces detach and project the droplets to the base metal) (NORRISH, 1992). The pulsed GMAW process works by forming one droplet of molten metal at the end of each pulse. Thus, the pulsed welding puts just the energy needed to detach the droplets and uses low levels of current when not extra power is demanded. This characteristic “cools” the weld pool down (makes it smaller), since the mean current is lower than in a similar conventional GMAW with spray transfer (PALANI; MURUGAN, 2006). This low level of mean current is what allows the

pulsed GMAW to be applied on thin materials, control distortions and run with low wire feed rates.

However, it is not so easy to set the parameters to obtain one droplet per pulse, since it depends on the welding condition (base material, electrode material and diameter, shielding gas, etc.)(PALANI; MURUGAN, 2006). Optimum pulsed transfer conditions are obtained by limiting the pulse duration t_p and the relationship $I_p^n t_p = D$ is often used to define the ideal one droplet per pulse condition. Here I_p is the pulse current amplitude (well above the spray transition current), n is a process dependent factor (usually between 1.2 and 2) and D is the detachment factor (related to the wire) (PALANI; MURUGAN, 2006; RICHARDSON et al., 2006). Although the relationship mentioned above is widespread, there is a study pointing out another relationship to achieve one droplet per pulse in welding of aluminium (VILARINHO; SCOTTI, 2000).

Norrish (1992) presents an approach to select the operation parameters for pulsed welding. Firstly the pulse current and duration must be selected from adequate droplet detachment charts (pulse current versus pulse duration map for one droplet per pulse). The second step is the specification of a suitable mean current for the application (considering the material, thickness, etc.). After that it is necessary to determine the required wire feed rate from a burn-off chart (wire feed rate versus mean current) for the wire of choice. Thus the required pulse frequency must be selected from a wire feed rate versus frequency chart. The final steps are the selection of t_b and I_b based on equations relating the parameters of the pulsed wave.

The general influence of the pulse parameters can be summarized as the pulse current and time being responsible for the metal transfer control while the background current and time being in charge of the heat input control. According to Stanzel (2007) it is alleged that pulsed GMAW is able to:

- Reduce spattering to nearly non-existent levels;
- Minimize distortion, compared to spray transfer mode;
- Create weld beads with good appearance;
- Weld thin metals;
- Allow all-position welding;
- Increase travel speeds (over short-circuit transfer).

Although the recommendation to operate in one droplet per pulse condition and the efforts to provide rules of thumb for that, there is no many other alternatives to check if the one droplet per pulse condition was achieved apart from using high speed filming. A novel

way to do that has been through arc luminescence analysis (MIRANDA et al., 2004). Jilong (1982) and Praveen; Kang; Yarlagadda (2006) in their analyses of metal transfer under pulsed conditions also found indications of one droplet per pulse circumstances. They identified visible marks (small peaks overwritten) in the voltage signals when the droplet is detached from the wire (Figure 2.17). The identification of these small voltage peaks is an alternative for rapid indication of one droplet per pulse state. This method, however, works with analogical power sources only.

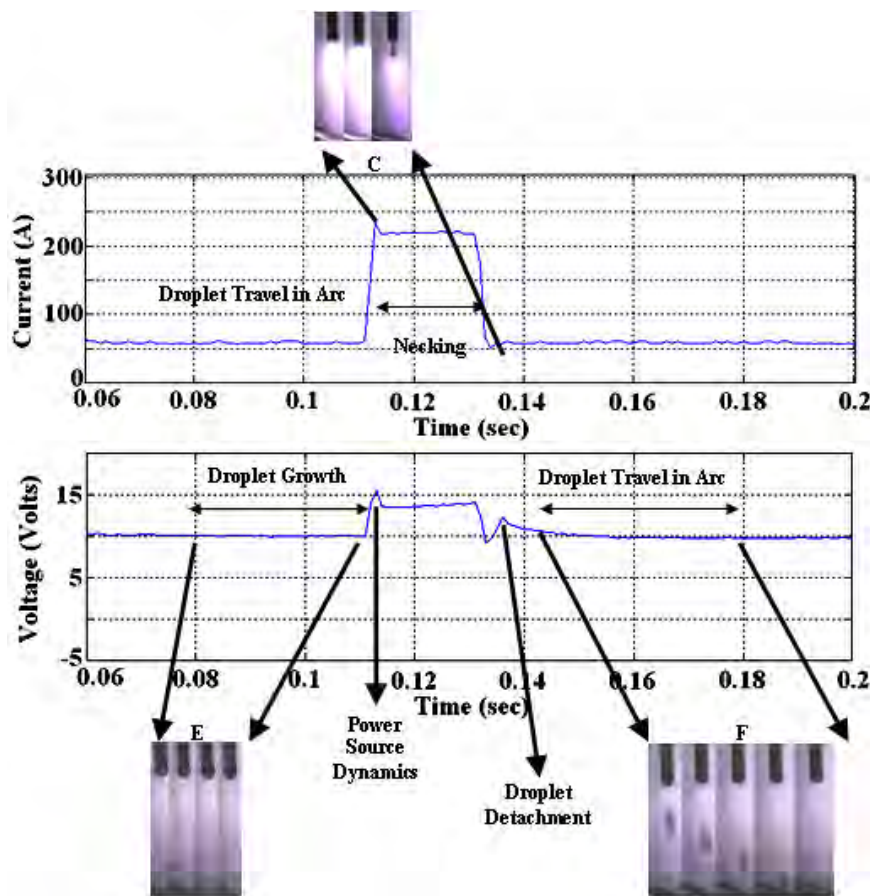


Figure 2.17: GMAW images synchronized with arc current and voltage waveform for one droplet per pulse (PRAVEEN et al., 2006)

Another option for tandem GMAW might be the use of alternate current (AC). This option has been used in single wire GMAW and has shown ability to produce welds with low heat input and shallow penetration in welding of thin sections (UEYAMA et al., 2004). This kind of pulsed welding is performed by setting the background current to the negative polarity in the welding circuit (electrode in the negative polarity) and the bigger the time in negative polarity in relation to the time in positive polarity, the shallower the penetration. Thus, the AC pulsed GMAW may also be an option for root runs, where the burn-through incidence is

always a challenge. Experiments conducted at The Edison Welding Institute (EWI) showed that AC GMAW was able to perform root runs of good quality on pipes. A root run welding without backing at travel speeds of 1.5 m/min was produced (Figure 2.18) (YAPP; BLACKMAN, 2003).

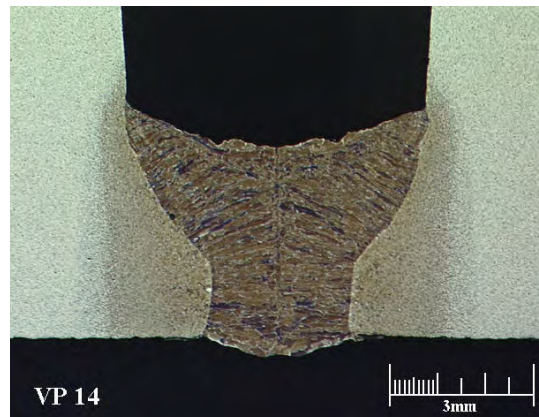


Figure 2.18: Root run with AC GMAW (YAPP; BLACKMAN, 2003)

2.2.3 Tandem GMAW advantages and limitations

Due to the tandem process versatility (independent settings for each arc), it has found more acceptance among welding costumers than the twin GMAW version. The main advantage claimed to tandem GMAW is the enhancement in productivity. With tandem GMAW is possible to achieve travel speeds in excess of 5 m/min (LINCOLN ELECTRIC, 2007c), but common values stay around 3 m/min (UEYAMA et al., 2005). This high velocity characteristic leads this process to automated applications and it is believed to be due to the high level of current used and to the formation of an elongated weld pool. As the base metal is exposed to the molten pool for a longer period of time, the welding travel speed can be increased to achieve a specified penetration, for instance. With an extended weld pool the arc force can be also distributed over a larger area of molten metal, which may result in less instability.

If the process is operated in low welding travel speeds high penetration in thick materials can be achieved. Metal deposition rates can be also high, reaching 15.9 kg/h, the level of spattering can be set low, the wetting at weld toes is improved and undercuts appear in very high travel speeds only (LINCOLN ELECTRIC, 2007c). This capability of avoiding undercut and lack of fusion defects may be due to the low current density in arc which is observed to have large cross sectional area, hence, the disruptive arc forces can be reduced. Another advantage of an elongated weld pool is the fact that the gases are given

more time and more area to escape, which reduces porosity (MICHIE et al., 1999). This information can, however, be doubtful, since there is also more area for the gases to get into the weld pool.

Despite these advantages, as parameters for two wires must be set, the tandem GMAW process tends to demand more training to operators than the traditional single wire GMAW. Regarding the high current levels employed, a close look to health and safety concerns is demanded as a general rule as well (higher shade number and fume extraction units should be considered, for instance). But probably the main disadvantages of the process are the initial cost and the tendency for interaction (interference) between the arcs. The initial cost can be rapidly supplanted by the high productivity achieved and a tendency of price dropping is expected as the diversity of equipments dedicated to this process has increased. In relation to the interaction between the arcs, this issue has been the target of a number of studies conducted by welding researches. Despite its rising importance for the industry, tandem GMAW process remains less well known than single wire GMAW, and information about it is more focused on economics and there are not many comparisons to single wire GMAW.

Generally, it has been claimed that the most common way of avoiding the interaction between the arcs and, therefore, stabilizing the metal transfer in tandem GMAW, has been through out-of-phase current pulsing. As the process uses two power sources, one is set as the master (responsible for command) and the other as the slave one (commanded). The power sources are synchronized in such way that while the current provided by the master power source is in the pulse time, the current supplied by the slave one is in the base time (the pulsing frequency for both electrodes is the same). It has been considered that by using such a method the magnetic interaction between the arcs can be minimized (UEYAMA et al., 2004), and that is the reason for less instability in out-of-phase welding. However, it has been found that this is not true for high mean current levels (SCOTTI et al., 2006). The authors showed that there is no evidence that out-of-phase current pulses can impose any reduction in the attraction of the arcs and droplets at high current levels. Although such work stated that there is no need for advanced power sources (out-of-phase capability) to reach sound welds, it confirms the importance of out-of-phase pulsing method to minimize arc interaction when the levels of current are not so high.

Even though out-of-phase pulsing is the most common method for stability improvement, the tandem GMAW process can also be employed with other different approaches in relation to the synchronism of the current pulses. As shown by Figure 2.19, the pulses can be staggered (out-of-phase pulses), simultaneous or with a specified delay between them. Ueyama et al. showed that a small delay (0.5 ms) between the pulses may

stabilize the process and avoid arc interruptions, allowing high welding travel speeds to be reached (UEYAMA et al., 2004).

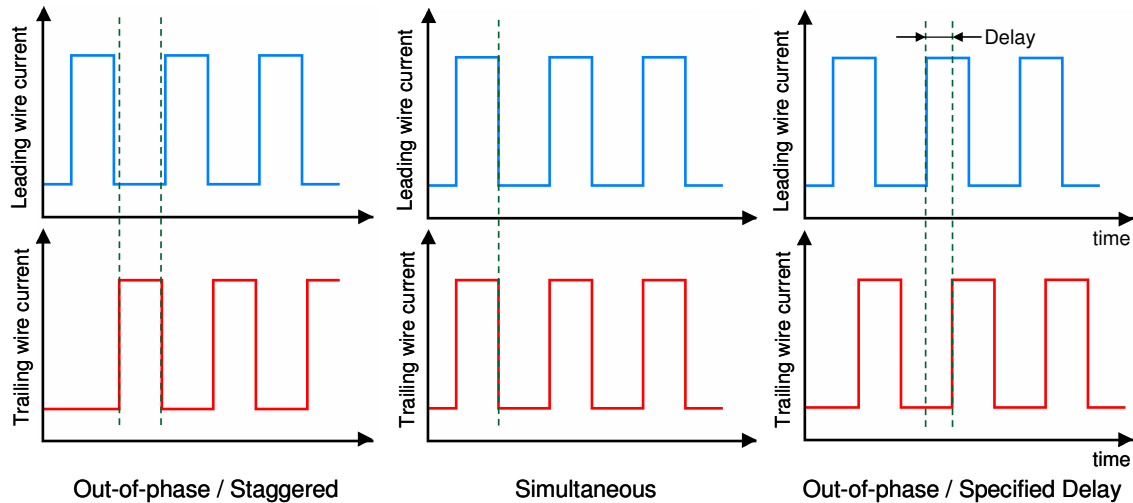


Figure 2.19: Different kinds of timing pulse controls applied in tandem GMAW

2.2.4 Parameters general influence

It has been mentioned that in pulsed tandem GMAW the leading arc is responsible to provide penetration while the trailing arc controls bead appearance. The functions of the leading electrode are to produce sufficient amount of molten metal with high currents and assure penetration in the base metal by its strong arc force and the functions of the trailing electrode are to prevent humping beads (maintaining the molten pool shape by its arc force and surface tension of the molten metal) and prevent undercut at the toe of the weld by filling molten metal (OHNAWA, 2003).

Ueyama et al. (2004) showed that, maintaining the leading wire perpendicular to work piece, the angle of the trailing wire determines the bead width and reinforcement. As the angle between the leading wire (upright) and the trailing wire is increased the reinforcement decreases and the bead width increases, while the penetration remains constant. According to the same authors this happens due to a raise of the horizontal component force of the trailing arc that increases the metal flow turning around the trailing arc. This result indicates that the trailing wire, otherwise the leading wire, does not interfere in the penetration. The ratio between the currents for the trailing and leading wires also plays an important role to increase the productivity of the process. It was shown that a relation between the trailing and leading wire currents of 0.31 to 0.5 maximizes the welding travel speed (UEYAMA et al., 2005). The typical defects found for a non-optimized current ratio were humping bead and undercut. The inter-wire distance has also to be optimized for a maximum welding travel

speed to be reached. This distance has found to be between 9 and 12 mm (MICHIE et al., 1999).

As the tandem process uses the same gas blends as the single wire GMAW version, the gas effects are expected to remain the same. The CO_2 effect of increasing the sidewall penetration and also the O_2 effect of decreasing the weld pool surface tension can be important for root run welding, since they can influence to build up the equilibrium of the weld pool in order to avoid burn-through and humping bead, for instance.

2.2.5 Difficulties in operating with pulsed mode in low mean current levels

Besides arc interference (attraction), which is well mentioned in the literature, problems of arc interruption may also arise in tandem pulsed GMAW when operating in low levels of mean current (UEYAMA et al., 2005). In contrast with the arc attraction phenomenon, the arc interruption in these circumstances is not commonly discussed in the literature. Ueyama et al. (2005) investigated the effect of some parameters on the number of arc interruptions (Figure 2.20) in tandem pulsed GMAW. The results demonstrated that these interruptions are related to abnormal arc voltages and occur frequently when one arc is in the pulse current and the other one is in the base current. They were verified under conditions with an inter-wire distance of around 10 mm (Figure 2.21) and with CO_2 presence in the shielding gas exceeding 10% (Figure 2.22). The number of arc interruptions was remarkably higher in the trailing wire than in the leading one. Taking these results into consideration, a short inter-wire distance and a low percentage of CO_2 should be used to minimize the number of interruptions, but the same authors (UEYAMA et al., 2005) showed that inter-wire distances between 9 and 12 mm and a shielding gas rich in CO_2 (20%) produced the highest travel speeds for welding of steel sheets.

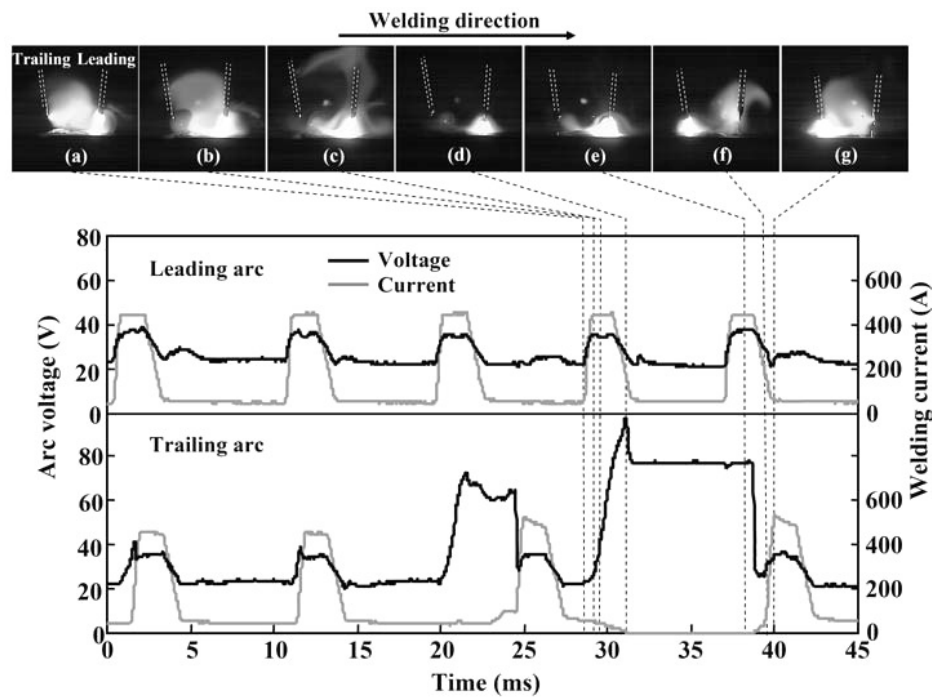


Figure 2.20: Typical current and voltage waveforms when an arc interruption occurs in tandem GMAW (UEYAMA et al., 2005)

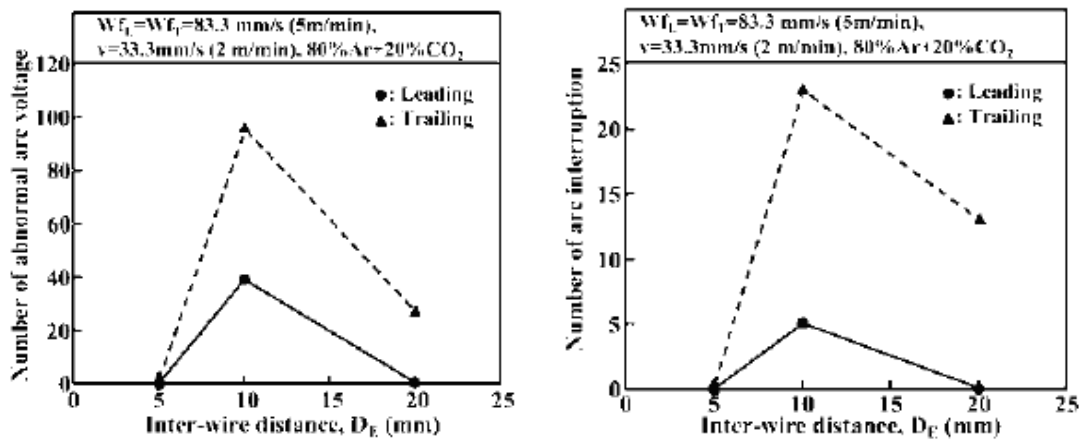


Figure 2.21: Effect of inter-wire distance on abnormal arc voltage and arc interruption occurrences in tandem GMAW (UEYAMA et al., 2005)

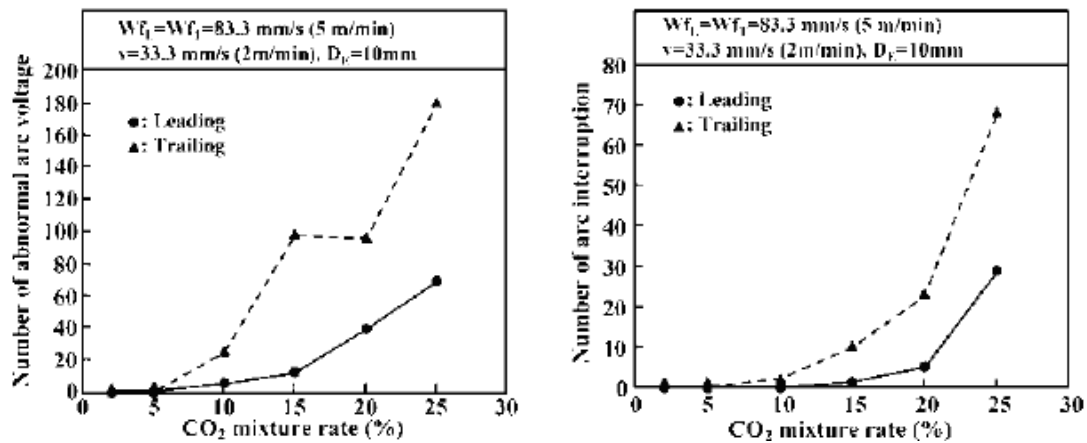


Figure 2.22: Effect of CO₂ mixture ratio on abnormal arc voltage and arc interruption occurrences in tandem GMAW (UEYAMA et al., 2005)

Ueyama et al. (2006) showed that the number of arc interruptions in the trailing wire decreased when the base current in this wire was raised from 45 A to 120 A (Figure 2.23). The increase in the base current value reduced the number of arc interruptions but a one droplet per pulse condition was no longer possible. It was observed that in all cases the abnormal arc voltage and arc interruption in the trailing wire occurred when the leading arc was in the pulse current and the trailing arc was in the base current period. This fact indicated that the trailing arc interruption may be related to the stiffness of the arc (low current results in low stiffness, allowing the arc to be easily disturbed). The deflection (or displacement) of the arc can be used to indicate the arc stiffness intensity (the bigger the displacement, the smaller the arc stiffness). Figure 2.24 presents a model for arc displacements in tandem GMAW based on the balance of electromagnetic forces and stiffness taking place in the arcs (UEYAMA et al., 2005).

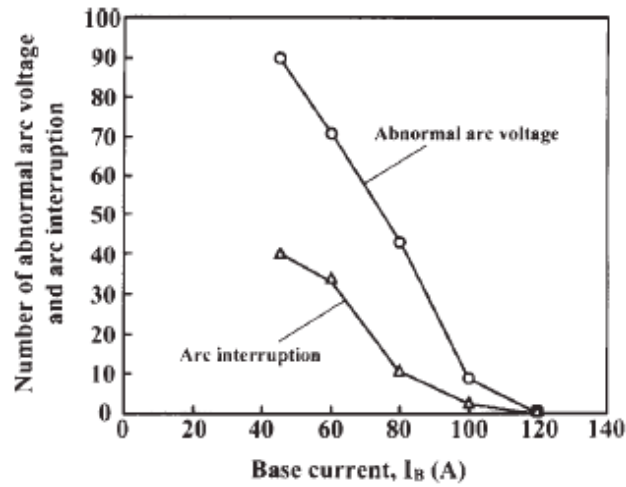


Figure 2.23: Effect of the trailing wire base current level on the number of abnormal arc voltage and arc interruption occurrences in the trailing wire in tandem GMAW (UEYAMA et al., 2006)

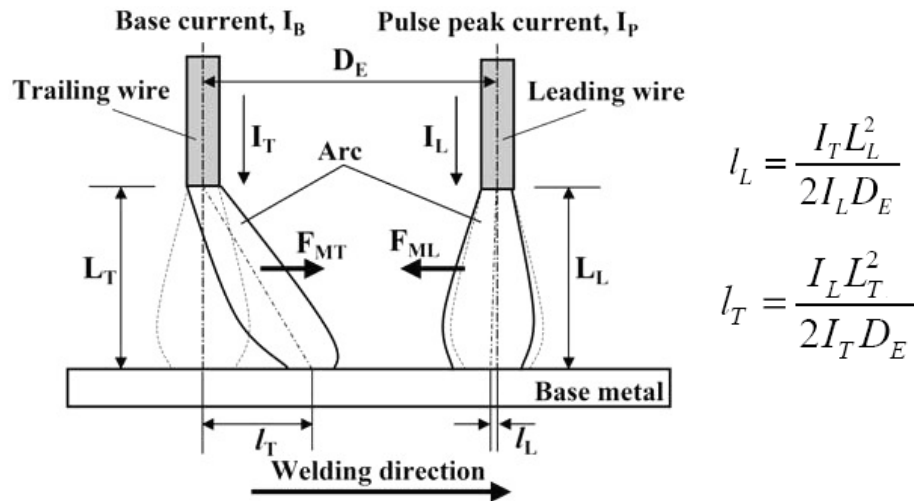


Figure 2.24: Model for arc displacements in tandem GMAW (UEYAMA et al., 2005)

Ueyama et al. (2006) also identified that when the pulse current is simultaneously output to both wires (in-phase pulsed welding) the incidence of abnormal arc voltage and arc interruptions were low. Figure 2.25 shows a comparison between the incidence of arc interruption in the trailing arc for in-phase (simultaneous-pulse control) and out-of-phase (staggered-pulse control) welding with an inter-wire distance of 10 mm and 20% or 25% of CO_2 in the Argon based shielding gas. The decrease in the number of arc interruptions was remarkably clear for the in-phase welding case. However, abnormal arc voltage and arc interruptions occurred sporadically.

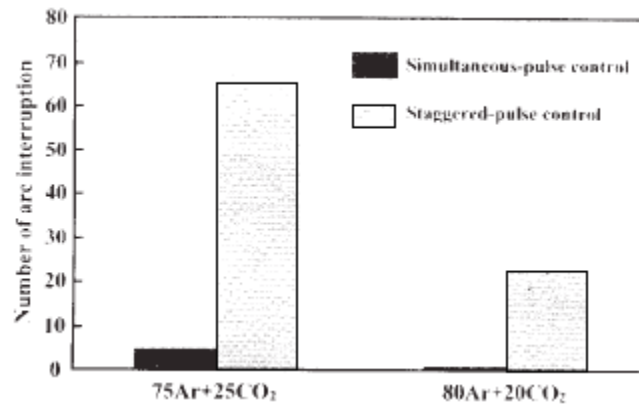


Figure 2.25: Arc interruption occurrences in the trailing arc for in-phase and out-of-phase tandem pulsed GMAW using different CO₂ percentage in the shielding gas (UEYAMA et al., 2006)

Based on the importance of the arc stiffness to avoid arc interruptions, a possible measure to avoid this inconvenience would be by forcing early output of the succeeding pulse in the current by observation of the arc voltage increase rate during the base current period (UEYAMA et al., 2006). However, this approach implies a temporary suspension of the synchronization between the wires and a control method in case of consecutive interruptions can be difficult and unreliable. Alternatively, Ueyama et al. (2006) practically eliminated arc interruption occurrences by means of a small delay between the pulses of current in the wires, using what could be called an “almost-in-phase” pulsed welding (the pulses of current flowing through both wires are slightly staggered). Figure 2.26 shows the small delay approach used and its degree of influence on the abnormal voltage and arc interruption occurrence. According to the authors, by using this method the cathode spots of the trailing arc are rapidly pulled back close to the molten pool and right below the arc by making use of arc stiffness (increasing the current level). A delay value around 0.5 ms was considered as adequate to avoid arc interruptions in both wires.

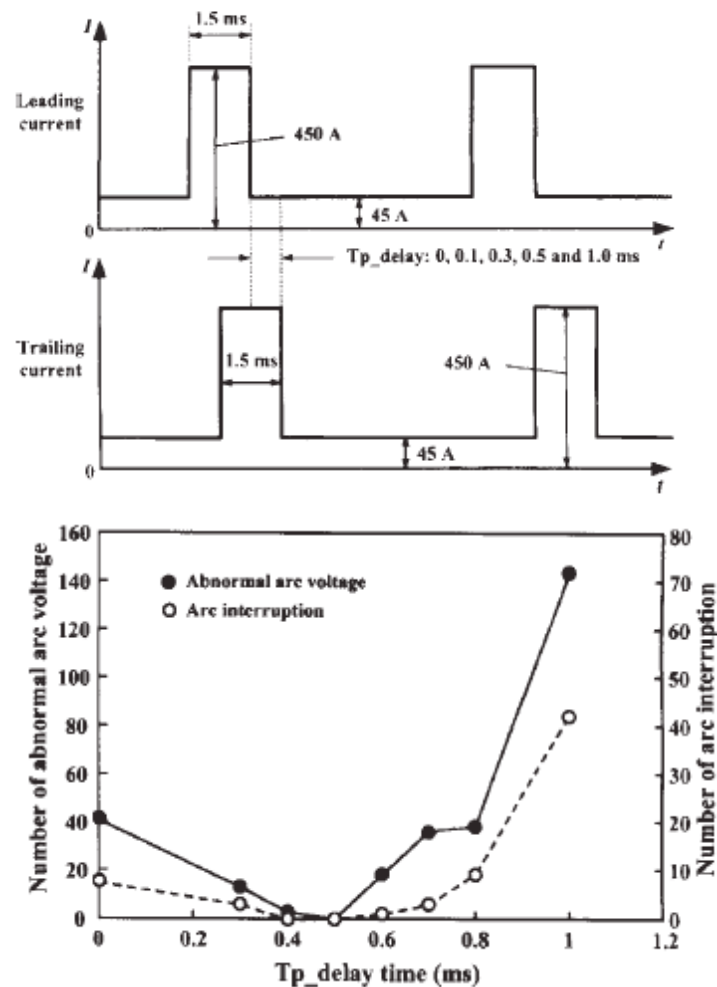


Figure 2.26: Method of small delay to avoid arc interruptions in tandem GMAW (above) and delay value influence on abnormal voltage and arc interruption occurrences in the trailing wire (below) (UEYAMA et al., 2006)

2.3 Laser - GMAW Hybrid Welding

Hybrid welding processes using Laser and arc processes have been developed for 30 years and their application has recently spread to the industry, mainly to the automotive sector. During the first ten years of development, the low Laser power available and the high cost of Laser equipments were, along with the lack of knowledge about the hybrid processes, certainly the main limiting factors. After 1990, the Laser - arc welding experienced a boom in research and development. Hybrid versions like Laser - TIG, Laser - Plasma and Laser - GMAW were highly developed. Although a variety of Laser - arc welding processes has been developed over the last three decades, several questions are still not answered.

As Laser is used in this work in a new approach for hybrid welding, a brief description of Laser beam welding is made. Special attention is given to Diode Laser, since it is the type

of Laser employed in the hybrid approach proposed. More details of Laser theory and application can be found in specialized literature. As the way the Laser beam is combined with tandem GMAW in this work is an innovation, a general discussion on Laser - GMAW is also presented as a basis to explore the new hybrid welding approach.

2.3.1 Laser Beam Welding

The early work with Lasers dates to the 60's. Following the advances made throughout the last decades, Laser systems have become more reliable and cheaper and their use has reached the most diverse areas, such as medical, military, electronics, communications, sensors and instrumentation, etc. The Laser use has become quite common in manufacturing as well, where it can be used, for instance, for surface treatment, cladding, cutting and welding. Lasers can be used for welding independently (Laser Beam Welding) or combined with other process (usually arc welding process) in the so-called hybrid welding.

The advantages and specially the limitations of Laser welding tend to be linked to the type of Laser used. However, general qualities and problems can be pointed. The primary advantage of Laser beam welding is the capacity of energy concentration. As the Laser beam is usually concentrated in a very small area, a high density of energy is achieved (increased travel speeds or deep and narrow welds). This characteristic leads to several other advantages. According to Booth (2004), due to the narrow deep penetration weld produced, Laser welding offers several advantages over other welding processes such as high joining rates, low consumable costs, high reproducibility, low manning levels, low levels of distortion (precision in assembly and reduction of rectification work).

Despite these advantages, the process faces two main limitations: high cost of equipments (including beam delivery and focusing systems) and low tolerance to joint misalignment and gaps. Since Laser beam welding produces narrow welds at high speeds, there is also a risk of welding defects such as lack of fusion, solidification cracks and porosity. Moreover, LBW (Laser Beam Welding) also faces difficulties when it comes to weld highly reflective materials such as aluminium and copper. During LBW the interaction of Laser beam, metal vapour and shielding gas produces induced plasma, which can reduce the process efficiency, since it blocks the beam (DAWES, 1992).

Autogenous Laser welding is currently extensively used in the automotive industry for fabricating tailored blanks. According to Booth (2004), in this case the process suffers from two drawbacks: the ability to bridge gaps is poor and the weld bead profile is frequently irregular when steel sheets of dissimilar thickness are joined. He also mentions that to overcome these limitations some methods have been developed to elongate the Laser spot

whilst keeping the overall spot size sufficiently small to maintain the welding at reasonable speeds. Elongation of the weld pool perpendicular to the direction of welding improves the capacity for gap bridging and, hence, enables fit-up tolerances to be relaxed. Analogously, elongation of the weld pool parallel to the direction of welding assists in the escape of gas bubbles and metal vapour. The technique thus reduces porosity. Elongation of the weld pool can be achieved using two Lasers with focused spots very close to each other or using a single Laser source with a beam splitter to generate two focused spots at predefined locations. Additionally, the Laser energy is not necessarily divided equally between the two spots; the energy can be apportioned between the two spots in any appropriate ratio. This is particularly useful when making butt welds between two sheets of different thickness. By using two Laser spots aligned perpendicularly to the direction of welding the majority of the energy can be directed to the Laser spot on the thicker plate, thus improving joint quality.

2.3.2 Type of Lasers used for welding

Almost all Laser systems commercially available for welding are CO₂ and Nd:YAG Laser sources. Although CO₂ and Nd:YAG Lasers are the most predominant systems for welding, they have been hampered by their size, complexity, high cost and their low efficiency. New systems such as high power diode Lasers have become recently available in the market as well. This kind of Laser has become even competitive with traditional CO₂ and Nd:YAG due to improved reliability, good life time and declining cost of diodes (STAUFER, 2007).

Low power diode Lasers are quite common and can be found in Laser printers and CD/DVD players, for instance. More powerful diode Lasers (usually up to 4 kW) are frequently used to pump other Lasers or in industry for cutting and welding operations. Also known as semi-conductor Lasers, these high power diode Lasers (HPDL's) use a semi-conductor diode material as its amplifying medium. They consist of a positive-negative junction within a multi-layer semiconductor structure. For processing of materials (cutting and welding), the semi-conductor material is based on InGaAs on a GaAs substrate or InGaAlAs on a GaAs substrate (TWI, 2008). They produce outputs with very large beam divergence because of diffraction. As a consequence, the resulting beam of these Lasers has a large angular spread compared to other types of Laser, which is a drawback in terms of focusability (TWI, 2008). Lenses for diode Lasers beam shaping are usually manufactured from glass or fused silicon. In order to achieve high power for manufacturing applications, the combination of several diode bars (forming stacks) is required. Commercial diode Lasers emit at wavelengths around 1,000 nm. Wavelengths at this level are invisible.

Diode Lasers have several advantages over CO₂ and Nd:YAG Lasers. They are extremely efficient, with 35% of the pumped energy being turned into output beam power (KENNEDY; BYRNE, 2003). Diode Lasers are also reasonably compact in size, their output beam can be delivered by optic fibre and they have nowadays a capital cost equivalent to CO₂ Lasers (KENNEDY; BYRNE, 2003).

2.3.3 Laser - arc welding

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. There have been described systems for hybrid welding combining Laser with GTAW (HU; DEN OUDEN, 2005), with PAW (PAGE et al., 2002, SWANSON et al., 2007), with GMAW (KIM et al., 2006, MULIMA et al., 2006) and even with SAW (TUSEK; SUBAN, 1999).

Regardless of the process of choice to be combined with the Laser, the general and eventual result is the increase in the effectiveness of the welding. It is well known that LBW is distinct for providing high power density, deep penetration, high welding speed, low distortion and precision. However, because of the small Laser beam spot, LBW shows poor gap bridge ability and precision in joint preparation is always a requirement. On the other hand, arc welding processes have relatively lower power density and produce wider weld beads, delivering good bridge ability for joint gaps and large tolerances for joint preparation. The combination of LBW and arc welding tends to enhance the advantages and compensate the limitations found in each process. The final result is an increase in the weld penetration depth, width and welding travel speed. Despite the lack of information on the use of Laser with tandem GMAW, a number of studies on hybrid welding with Laser and single wire GMAW (Figure 2.27) have been published, most of them using CO₂ or Nd:YAG Lasers. Figure 2.28 shows a welding operation using Laser - GMAW hybrid process and Figure 2.29 shows a commercial head devised for this process.

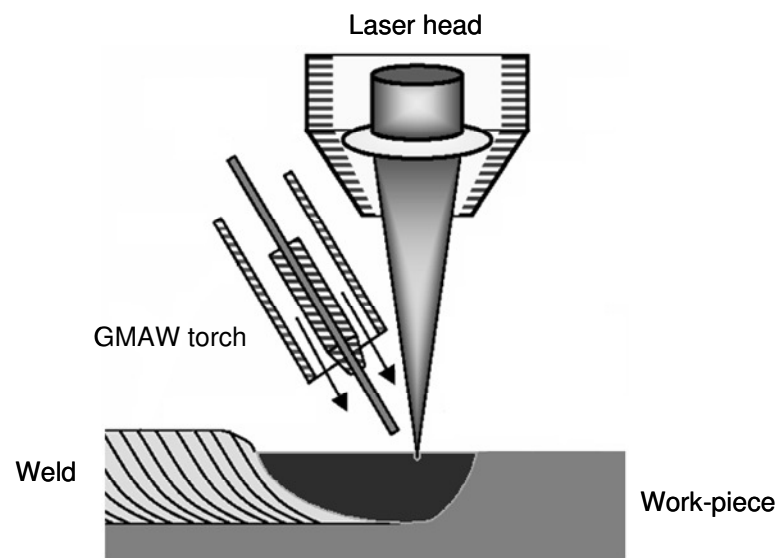


Figure 2.27: Typical hybrid Laser - GMAW arrangement (Booth, 2004)



Figure 2.28: Welding operation using Laser - GMAW hybrid process (BWI, 2008)



Figure 2.29: Commercial head devised for Laser - GMAW hybrid process (Fronius, 2008a)

According to Booth (2004), if compared with the use of Laser power alone, hybrid Laser - arc welding offers:

- Increased travel speed (2 times) or increased penetration (1.3 times) (Figure 2.30);
- Improved tolerance to fit-up gap;
- Ability to add filler material to improve weld metal microstructure, joint quality and joint properties;
- Potentially improved energy coupling;
- Increased heat input and reduced hardness.

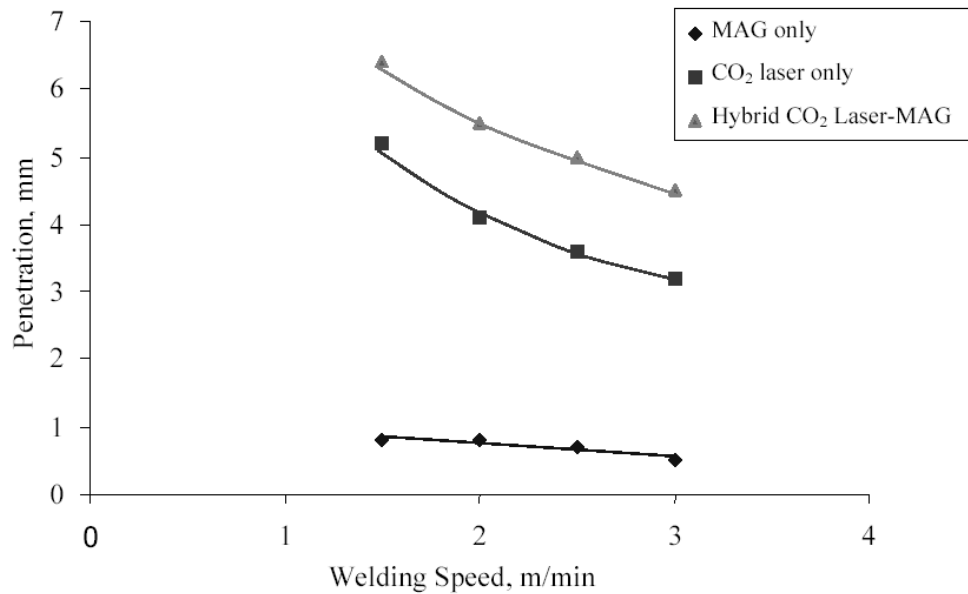


Figure 2.30: Comparison of welding speed and penetration for single and hybrid processes (steel) (Booth, 2004)

However, Booth also points some drawbacks, which include increased complexity, the need to define additional welding parameters and the requirement to establish the process parameters anew as these cannot be determined simply from the optimum procedures for the two separate processes. Nevertheless, he says that the hybrid Laser - arc welding is now a production process in both the automotive and shipbuilding industries and has been shown to be a candidate process for girth welding of gas transmission pipelines. The high cost added by the Laser part of the process is certainly another great limitation and the spatters that may be generated during the hybrid welding process, mainly due to the GMAW process, is likely to damage optical components in use with the Laser.

Tusek and Suban (1999) cite that the main advantage of the use of both heat sources is the more efficient use of the energy supplied. With certain parameters, the quantity of molten material increases by 100% compared with the sum of the individual quantities of molten material in the individual processes. The synergic action of the Laser beam and welding arc shows that the Laser beam in the welding arc, when current intensities are low, affects ionisation, reduces arc resistance, and increases the number of carriers of electrical current. However, according to Tusek and Suban (1999), it is not understood which property of the Laser beam contributes the most to the higher ionisation; whether it is the higher concentration of heat energy alone or to some extension the presence of electromagnetic waves with short wavelength.

Hu and den Ouden (2005) studied the influence of Laser radiation on the stability of the welding arc. The experiments were conducted using a low power (500 W) Nd:YAG Laser in

combination with a GTAW arc. It was found that the stabilising effect can be explained in terms of two phenomena: the absorption of Laser energy by the arc plasma and the change of the arc plasma composition caused by strong evaporation of workpiece material. Both phenomena lead to a reduction of the effective ionisation potential of the plasma and thus provide a more conductive, stable plasma channel for arc root and column that overcomes disturbance by external forces.

Qin; Lei; Lin (2007) studied the effects of hybrid Nd:YAG Laser - pulsed GMA welding parameters on the weld shape using bead-on-plate tests. The results indicated that the Laser energy mainly decides the weld penetration and that the weld width depends on the arc process for a given welding speed. The distance between the Laser spot and the arc, and the location of the Laser focus also had some effects on the hybrid weld appearance. The addition of Laser energy into pulsed GMAW can greatly increase not only the weld penetration, but also the welding speed, and it can also improve the weld appearance for low welding currents.

Kim et al. (2006) carried out experiments with Laser - GMAW and found that the heat input delivered to the plate is dependent on the nature of the leading heat source (Laser or GMAW) and also the joint condition used in the hybrid set-up. Synergic effects of the two heat sources are maximised when the Laser beam is located between the arc centre and the impact point of the molten droplets within the weld pool. The final bead shape in hybrid welding is influenced by the volume of the molten pool before the impingement of the Laser beam. That is, 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. The weld bead shape was also found to be dependant on other features of the welding process such as joint gap condition, leading heat source and preheating effects.

Despite the fact LBW is largely used in combination with pulsed GMAW, Mulima et al. (2006) presented the first trials using Laser (Diode) combined with GMAW in a controlled short-circuit transfer mode. The objective was to verify the possibility of improving the joint completion rate and produce deep penetration welds at higher travel speeds. The controlled short-circuit transfer is well known for the capacity of delivering a controlled heat to the workpiece and absence of spatters. It was shown that the welding travel speed is significantly increased or deep penetration achieved, both known as limitations of the controlled short-circuit transfer process.

The hybrid process has become even an option to be used in pipeline applications, where the demand for high speed welding is always present. According to Moore; Howse; Wallach (2004), Laser - arc hybrid welding is shown to be a process that can generate good quality welds in commercially available pipeline steels. It also has the potential to complete

girth welds in these steels with significantly fewer welding passes than are currently required for arc-welded pipelines, reducing the joint completion time. The high penetration possible with hybrid Laser - arc process prevents the problems associated with the rapid cooling and solidification crack susceptibility of Laser welding, while maintaining the advantages of deep penetration depth or fast travel speed from high-power Laser welding.

2.3.4 Welding speed in Laser - arc hybrid welding

The need for high welding travel speeds, keeping high deposition rates and penetration capabilities, has driven the search for new welding processes or improvements in the existent ones. The hybrid welding with Laser and GMAW seems to fill this requirement very well. A welding travel speed increase of up to 90 % relative to the welding with Laser and cold wire has been reported (NIELSEN et al., 2002).

Another study shows an increase in welding travel speed from 1 m/min to 2.6 m/min when Laser with cold wire is replaced by Laser - GMAW (DILTHEY; WIECHEMANN, 1999). The key for the high welding speed capability of Laser - GMAW seems to be the ability to avoid humping formation (BAGGER; OLSEN, 2005). The formation of humping is typical to practically all the welding process when high welding travel speeds are attempted (SCOTTI, 1991, REIS, 2005). The hybrid process has been used with the Laser beam defocused and at a short distance in front of the leading edge of the GMAW weld pool by Bagger and Olsen (2005). The beam power and spot size were varied in tests and, given a GMAW process condition, bead humping formation was suppressed by Laser heat input of sufficient power density (relationship between power intensity and beam spot area). Comparison of the tow angles of humped and non-humped weld beads suggested that capillary instability was a factor likely to contribute to weld bead hump formation. 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. According to their work the humping is avoided by applying a Laser beam with intensity and spot size sufficient to provide a bead width large enough to prevent capillary instability.

Regardless of humping occurrence, generally in arc welding the bead shape becomes more uneven as the welding travel speed increases. Figure 2.31 shows the welding speed limits under which uniform weld beads are produced by hybrid and arc welding. In this case the welding speed limit for hybrid welding is at least seven times higher than that for arc welding.

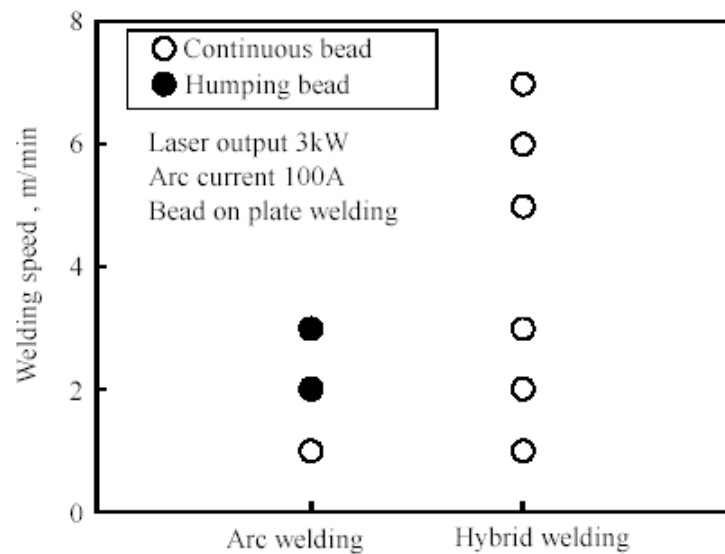


Figure 2.31: Welding speed limit for arc welding and hybrid welding (ONO et al., 2002)

2.3.5 Gap tolerance (bridgeability) in Laser - arc welding

The gap tolerance of a welding process can be defined as the ability the process has to join (bridge) the molten sides of a joint and keep this union stable until solidification takes place. This ability is often measured through the maximum gap allowed for a determined welding package (process and parameters). Figure 2.32 gives an idea on how the welding process determines the gap tolerance.

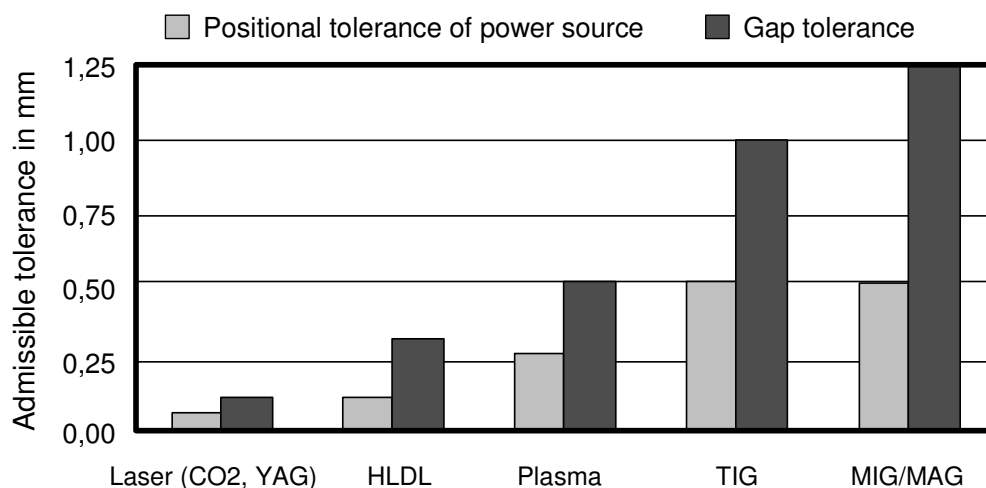


Figure 2.32: Gap bridgeability and positioning requirements for different welding processes (HLDEL: a kind of LBW with Diode Laser) (KUTSUNA; LIU, 2007)

The Laser process has a very low gap tolerance and the GMAW process has a high gap tolerance. This can be explained in part due to the use of filler metal in the GMAW process,

which works as a mass of material to fill up the empty space left by the gap. In order to improve the gap tolerance of Laser welding, filler wire, including cold wire (JOKINEN; KARHU; KUJANPAA, 2003, SUN; KUO, 1999) and hot wire (XIAO et al., 2004), has been attempted. The wire feed speed seems to be a limitation of these approaches since they rely on part of the Laser beam energy to melt the wire. This may have been one of the forces driving investments in Laser - GMAW. Laser - GMAW can feed more wire to the molten pool and the gap bridging ability can be improved. Numerous studies have been conducted on this topic. Figure 2.33 shows the correlation between maximum welding speed and gap width in CO₂ Laser - GMAW.

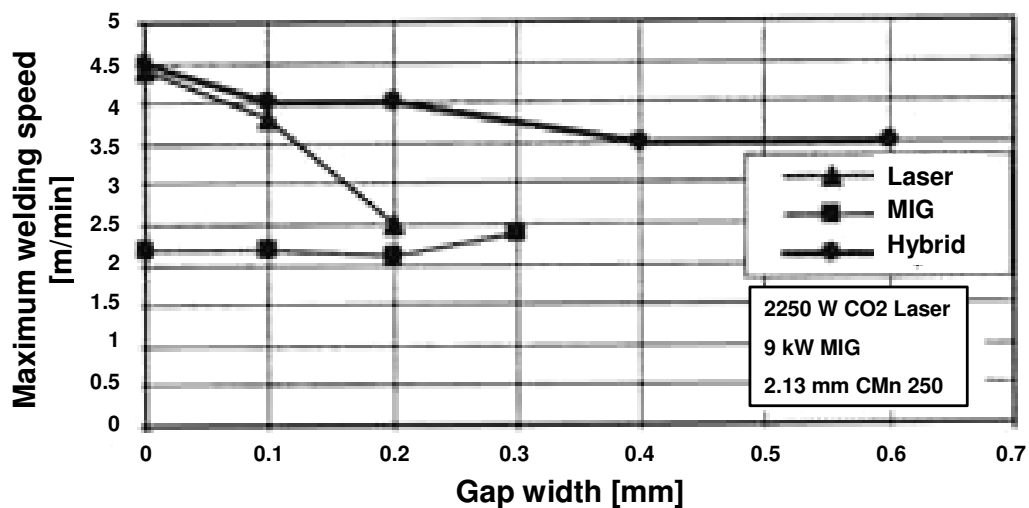


Figure 2.33: Maximum welding speeds obtainable at various gap distances in butt welding using Laser, GMAW and Hybrid processes (BAGGER, 2003)

Laser - GMAW has shown good bridging ability even in lap joints. Figures 2.34 and 2.35 present, respectively, gap tolerance in Laser welding and in Laser - GMAW for lap joints. It is clear that the gap tolerance for hybrid welding is higher than that for Laser welding. When the gap is present in Laser welding without filler metal the amount of molten metal tends to be insufficient to fill the empty space, resulting in lack of filling or burn-through (ONO et al., 2002).

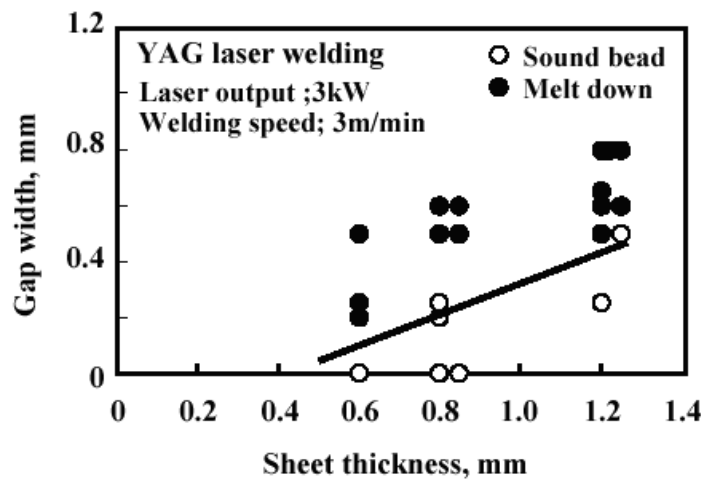


Figure 2.34: Gap tolerance in Laser welding of lap joints (ONO et al., 2002)

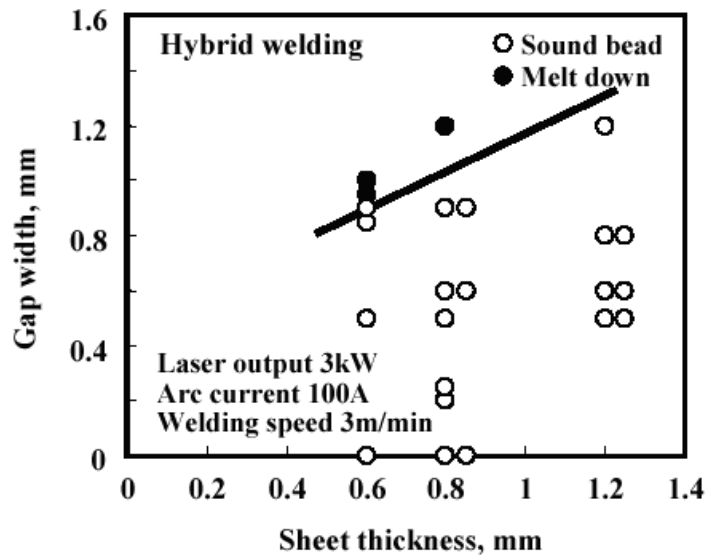


Figure 2.35: Gap tolerance in Laser - GMAW of lap joints (ONO et al., 2002)

2.3.6 Reduction of porosity formation

One of the recurrent defects in Laser welding is porosity due to the high power density and deep penetration achieved. As the cooling rate is usually very high, there is no time for the gas bubbles to escape. This problem tends to be minimized in hybrid welding. Figure 2.36 shows X-ray inspection images of weld beads produced with Laser and Laser - TIG welding (NAITO; MITSUTANI; KATAYAMA, 2006). Comparing to the Laser welding, the amount of porosity increased when the TIG current was 100 A and decreased when the current was set to 200 A. According to the authors, the fall in the level of porosity may be explained through the shape of the weld pool and consequent material flow pattern. The weld beads produced with the hybrid process with arc current at 200 A were wider than those produced by Laser or

hybrid welding with an arc current at 100 A. Probably this happened because in the GTAW fluid flow changes from laminar to turbulent at around 100 A. Figures 2.37 and 2.38 illustrate how the flow pattern in the weld pool can be dependent on the welding process used. According to the model, in the case of Laser welding the molten metal tends to rotate at the bottom of the molten pool with the gas bubbles formed following along and eventually getting trapped in the weld bead. In contrast, in hybrid welding the molten metal flows from the surface to the bottom of the molten pool and back. In this case, the bubbles formed at the bottom of the pool flow along with the molten metal and escape.

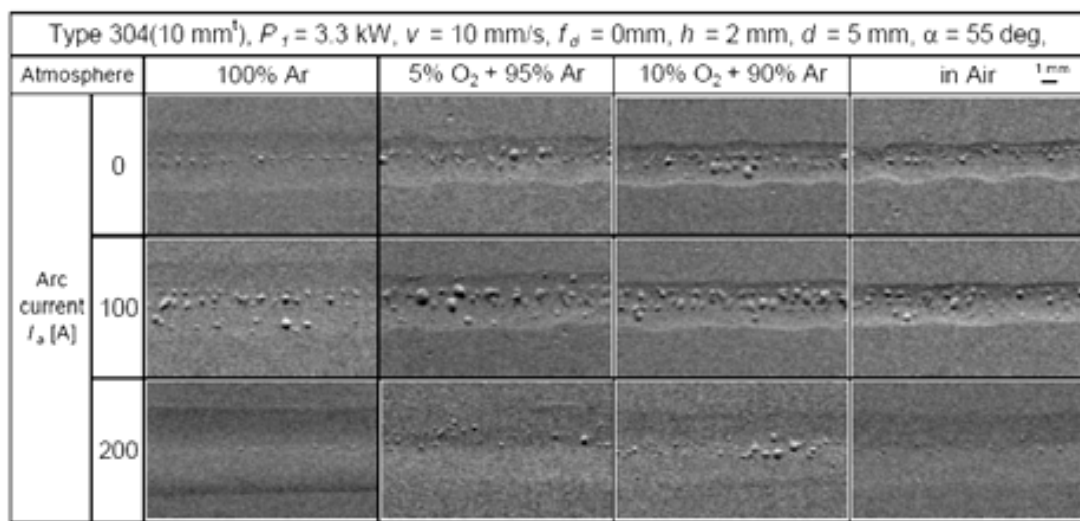


Figure 2.36: X-ray inspection images showing porosity formation tendency in Laser and in hybrid welding (NAITO; MITSUTANI; KATAYAMA, 2006)

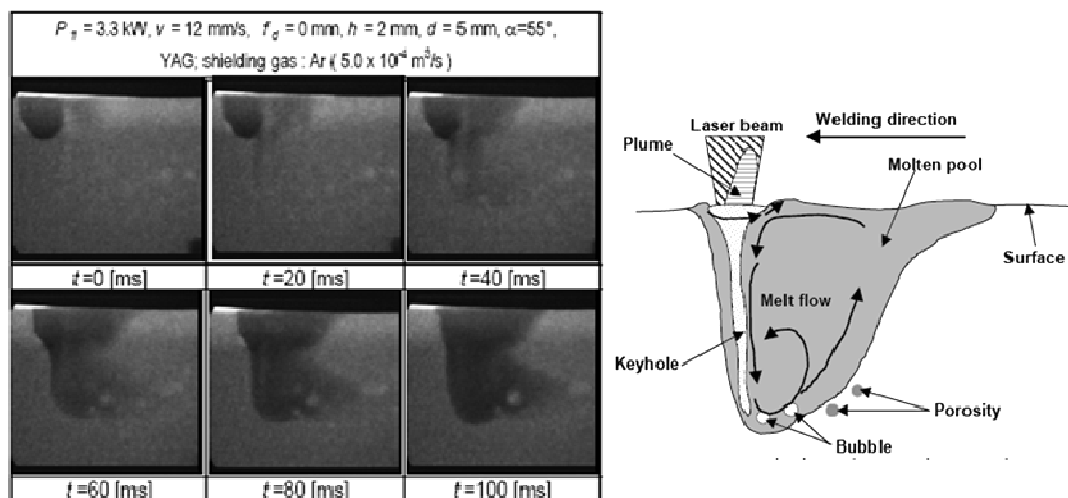


Figure 2.37: X-ray transmission observation in YAG Laser (NAITO; MITSUTANI; KATAYAMA, 2006)

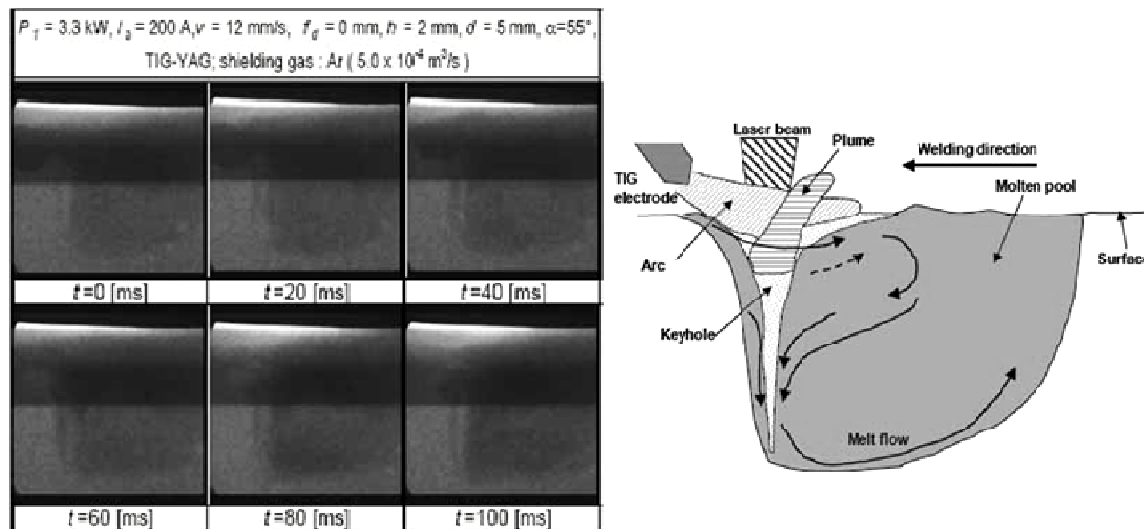


Figure 2.38: X-ray transmission observation in hybrid welding (NAITO; MITSUTANI; KATAYAMA, 2006)

2.3.7 Effects of hybrid welding parameters on the weld bead

The analysis of the influence of the welding parameters in hybrid welding is not as simple as joining the influence of the processes individually. There is a synergic effect present in the hybrid process, which plays an important effect. The following items present an overview on the effect of some parameters on the weld profile and quality.

Laser - arc arrangement

One of the first questions to emerge when dealing with hybrid welding is about which process should lead; whether the Laser or the arc process. There have been a number of researchers studying the Laser hybrid welding. Some of them tried the Laser as the leading process (ENGSTROM et al., 2001, KUTSUNA; CHEN, 2002, UCHIUMI et al., 2004) and some others the arc as the leading process (NAITO et al., 2004, ARIAS et al., 2005, LIU; KUTSUNA, 2005).

By studying the influence of the process arrangement on the bead shape Abe et al. (1996) showed that the fact of placing the Laser first (leading the process) improved the bead shape in relation to the situation with the arc process first. Nielsen et al. (2002) showed that the penetration was increased by 10% if the GMAW source is placed after the Laser. However, in another study, Beyer et al. (1994) used CO₂ Laser - GMAW to show that the penetration depth practically did not vary regardless of using the Laser to lead or the arc process to lead (Figure 2.39). This fact is reinforced by Figure 2.40.

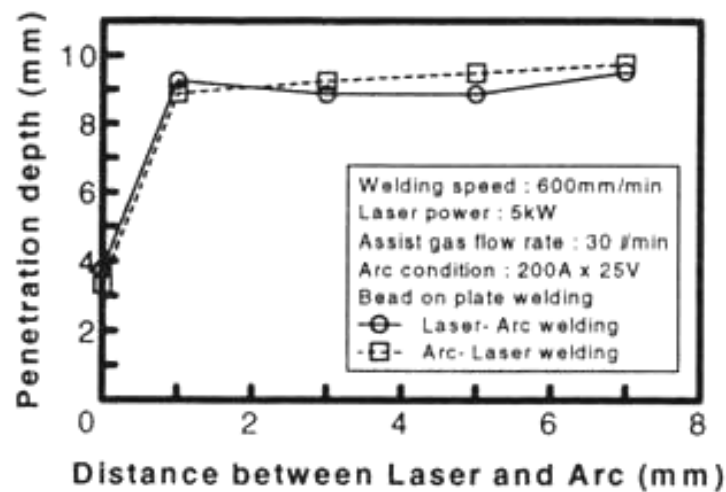


Figure 2.39: Influence of the process arrangement and distance between the processes on penetration depth (BEYER et al., 1994)

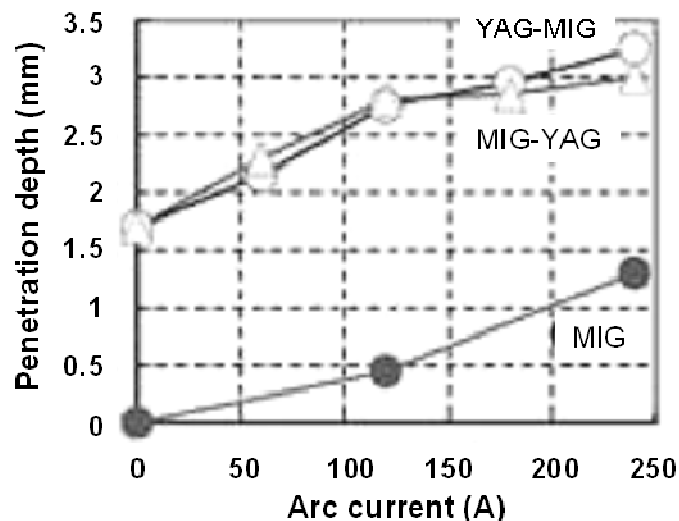


Figure 2.40: Penetration in MIG, MIG-YAG and YAG-MIG at different levels of arc current (Naito et al., 2002)

Distance between the Laser beam and the arc

Another parameter that exerts influence on the weld bead is the distance between the Laser beam and the arc. This distance can be defined as the distance between the Laser beam spot and the electrode prolonged axis at the workpiece (MAGEE; MERCHANT; HYATT, 1990) or between the Laser spot and the discharging point of the arc on the workpiece (JOKINEN, 2204). It has been a consensus that the best results in Laser hybrid welding are achieved when the plasmas of the individual processes are combined, which means, in turn, a certain limit for the distance between the Laser and the arc. According to

Kutsuna and Liu (2007), if the distance is too large the two processes act individually and cannot affect each other. However, the Laser and the filler metal should not be too close in order to avoid disturbance of the keyhole made by the Laser beam. This means that the arc (filler metal) should not be introduced into the Laser spot. On the other hand, in general deeper penetration is achieved when this distance is shortened (Figures 2.41 and 2.42). However, this effect is also dependent on the type of Laser used, for instance. Table 2.1 presents optimum distance values between the Laser beam and the arc for different processes combination.

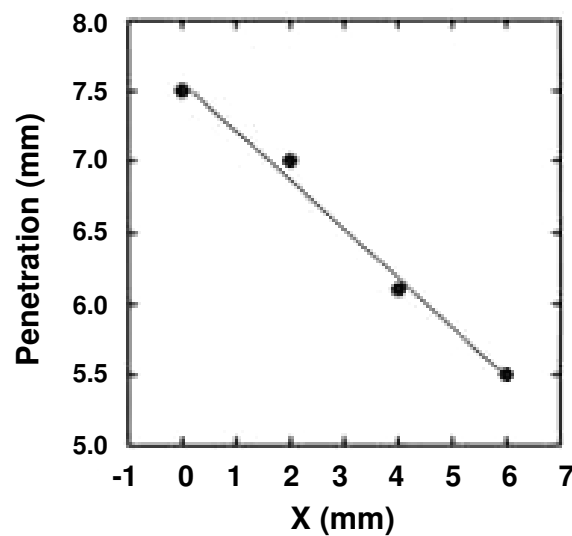


Figure 2.41: Influence of the distance (x) between the Laser beam and the arc on penetration in hybrid welding (MAGEE; MERCHANT; HYATT, 1990)

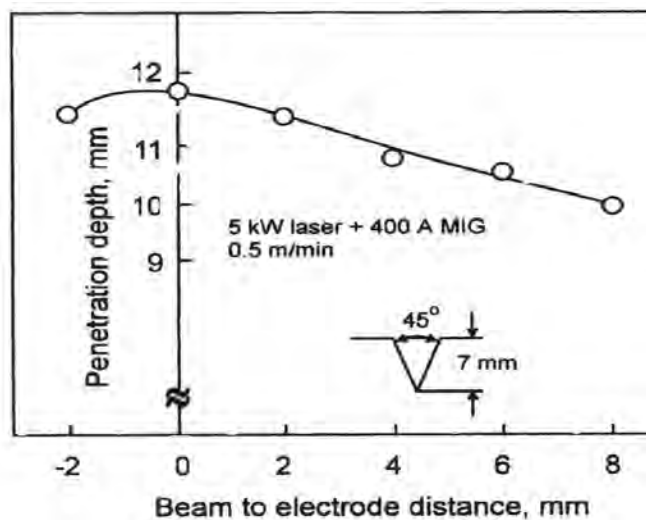


Figure 2.42: Decline in penetration depth as the distance between the Laser and the arc is increased in hybrid welding (MATSUDA et al., 1988)

Table 2.1: Optimum distance values between the Laser and the arc process in hybrid welding
(KUTSUNA; LIU, 2007)

Relative distance (mm)	Laser	Second energy source	Material
1-2	12 kW CO ₂ laser	6-8 kW MAG	12mm C/Mn steel
1-3	4.8 kW CO ₂ laser	5 kW GMAW	6 mm RAEX 275 MC
0	5.7 kW CO ₂ laser	<17 kW GMAW	Up to 25mm CSA 640.21/M
2	3.5 kW YAG	3 kW TIG	5mm A6061
2	3 kW YAG	1 kW MIG	4 mm AlMg ₃
2	3 kW YAG	3.4 kW MIG	5 mm SS304
2	1.8 kW YAG	0.6-0.7 kW TIG	5 mm SS304

Figure 2.43 shows the influence of the distance between the Laser and the arc on penetration in 3 kW YAG Laser - GMAW. The penetration increased when the beam was put either at 2 mm behind the arc or at 2 mm ahead of the arc. In contrast, the penetration decreased when the Laser beam spot and the arc central root were aligned. This fact indicates that more Laser energy may have been used to melt the wire or to overheat the molten pool. The penetration also started to decline when the distance was increased even further (4 or -4 mm), which means that the hybrid process was getting 'less hybrid'.

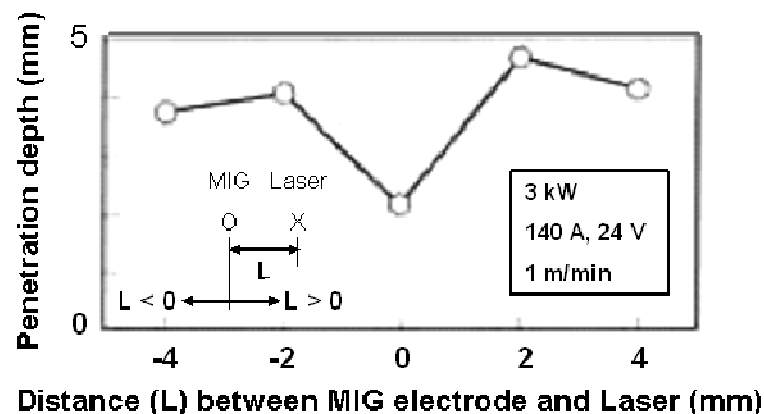


Figure 2.43: Influence of the distance between the Laser beam and the arc on the penetration depth (Nd:YAG Laser - MIG) (ISHIDE, 2001)

Concerning the distance between the Laser and the arc, in general it can be said that by shortening the distance between the two sources of energy up to a certain limit seems to increase the weld penetration. When the distance is increased there is a point beyond which the two energy sources start to act independently and the process cannot be regarded as hybrid anymore.

Focal point position (defocusing distance)

In the case of LBW the Laser energy (density) achieves its maximum at the focal plane and decreases along the beam axis in either direction as the beam diverges. Studies carried out on LBW have revealed that the Laser beam focal position should be below the material surface to achieve maximum penetration (DULEY, 1999). Figure 2.44 shows the results found. The negative focal point values refer to distances below the workpiece surface. Further studies reveal that the thermal deformation suffered by optical components under operation shifts their focal point upwards (CHEN; FANG; LI, 2004). To correct this discrepancy 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 may be an explanation for the results found regarding the Laser beam focal point position.

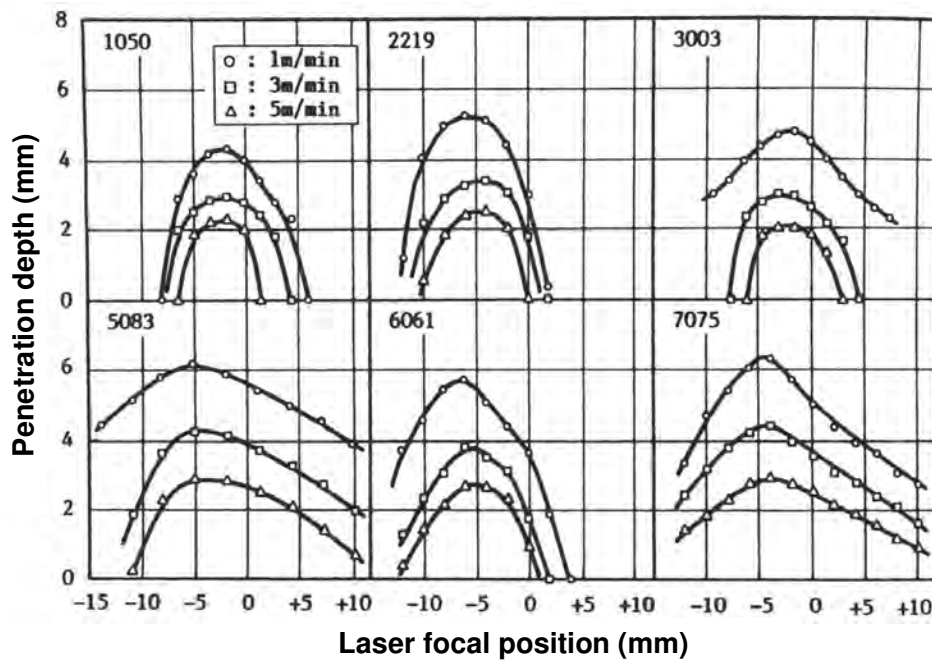


Figure 2.44: Influence of Laser focal point position on penetration depth in LBW for different materials (DULEY, 1999)

When it comes to hybrid welding, the same effect seems to occur (Figure 2.45). If the position of the Laser beam focal point is brought into the workpiece up to a certain limit, the penetration depth is increased. Ueyama et al. (2004) noticed that too much defocusing (moving the focus point) into the workpiece widens the bead and decreases penetration depth. Further defocusing beyond the value needed to compensate any effect caused by

thermal deformation in the optical system may lead to loss of the Laser beam energy density, this is, wider and shallower welds.

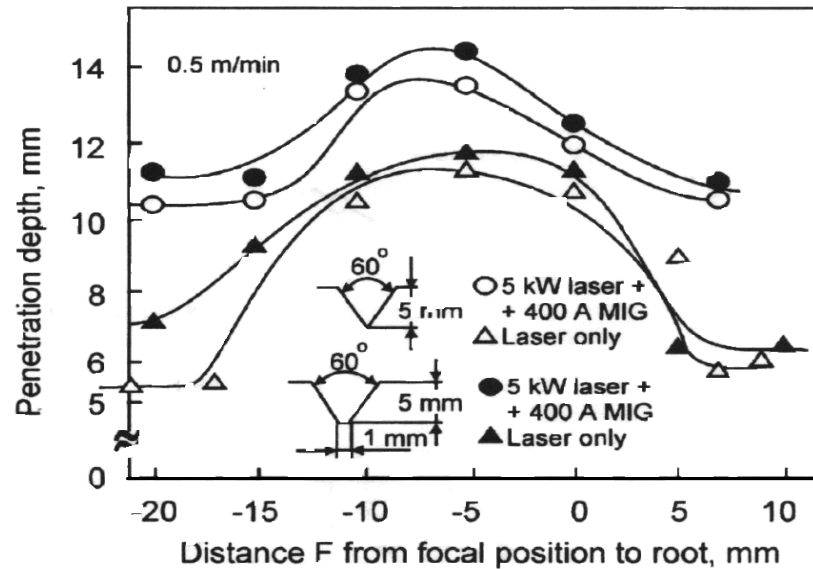


Figure 2.45: Influence of Laser beam focal point position on weld bead penetration in hybrid welding (CO₂ Laser) (MATSUDA et al., 1988)

2.3.8 New developments in Laser - arc hybrid welding

Following the advances in hybrid welding processes, a process using Laser and two GMAW arcs has been developed (WIESCHEMANN; KELLE; DILTHEY, 2003). The HyDRA (Hybrid welding with Double Rapid Arc) process has been able to bridge gaps of more than 2 mm at roots of joints prepared in V without any weld pool support and in one pass for a thickness of 5 mm. In this process all the three welding heat sources act in one zone and the geometrical arrangement of the individual components is of central importance. Figure 2.46 shows a comparison of the weld cross sections and welding conditions in SAW (Submerged Arc Welding), Laser - arc hybrid welding and HyDRA welding.

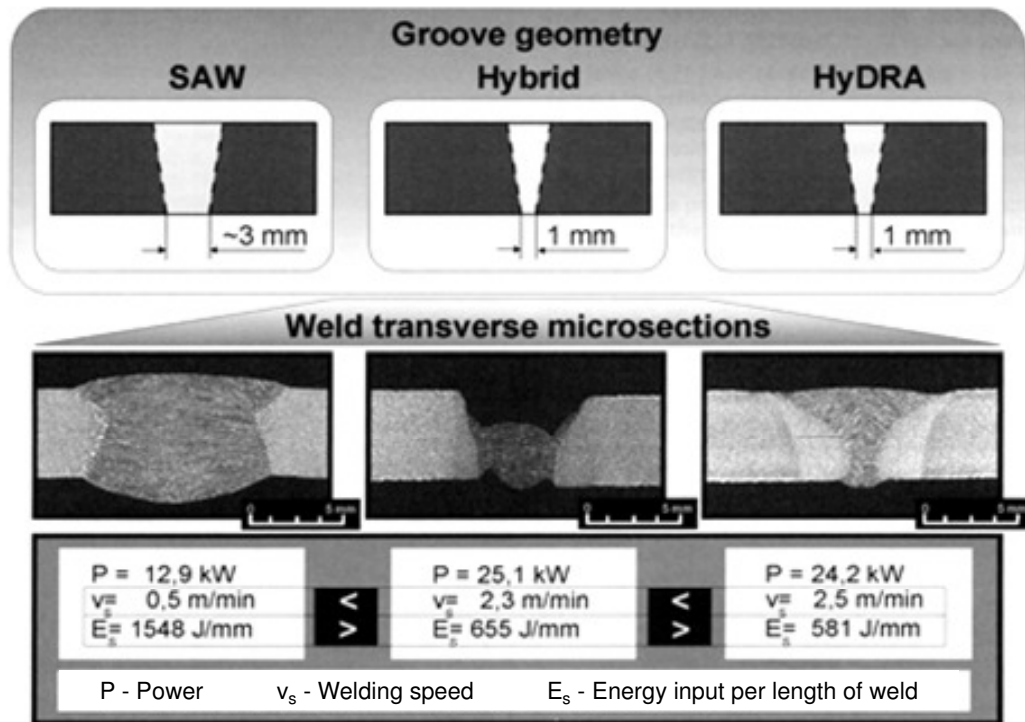


Figure 2.46: Weld cross sections and welding conditions in SAW, Laser - arc hybrid and HyDRA welding (WIESCHEMANN; KELLE; DILTHEY, 2003)

In the same line as the idea of using more than one arc process combined with the Laser beam, another new version for hybrid welding has been developed using Laser and three arcs (FRONIUS, 2008). In this case the Laser is combined with a GMAW torch and with a tandem GMAW torch. Figure 2.47 shows the schematic illustration of the Laser - GMAW - tandem GMAW process and Figure 2.48 shows the head devised for this process. According to the manufacturer, this process offers high welding speeds coupled with good bridging ability and good metallurgical properties. The leading process formed by a Laser beam and one GMAW arc results in a very narrow heat-affected zone with a large ratio of weld penetration to weld width. The trailing tandem GMAW process has a significantly lower energy density and is characterised by a very high deposition rate. The process enables steel sheets with a wall thickness of 8 mm, for example, to be welded at enhanced welding speeds. The leading Laser - GMAW process is used for welding the root, and the trailing tandem GMAW process for welding the top pass. Figure 2.49 shows a cross section of a weld produced by this process.

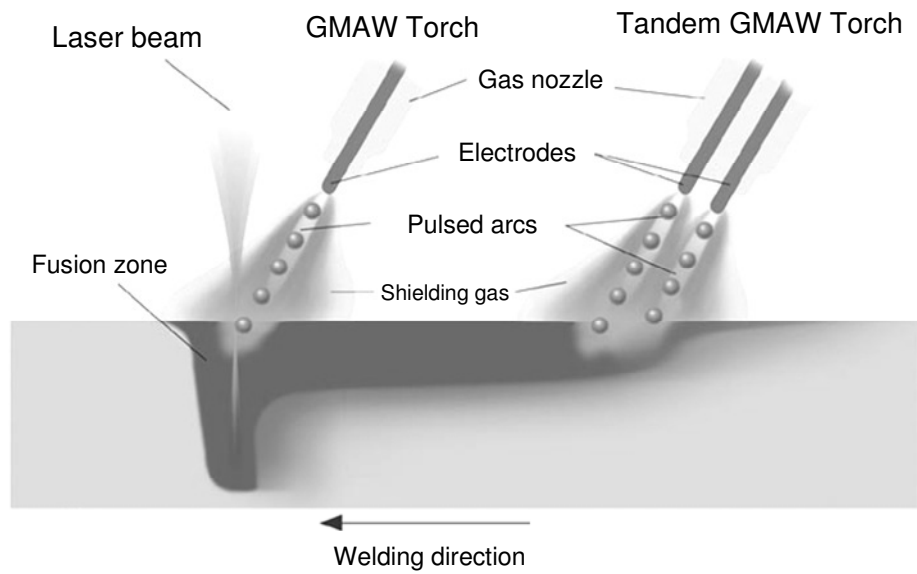


Figure 2.47: Schematic illustration of the Laser - GMAW - tandem GMAW process (FRONIUS, 2008b)



Figure 2.48: Head devised for the Laser - GMAW - tandem GMAW process (FRONIUS, 2008b)

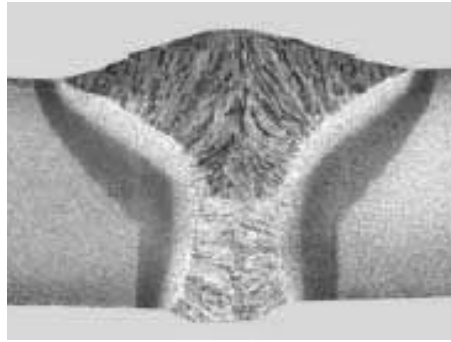


Figure 2.49: Cross section of an 8 mm thick plate welded at 1 m/min using the Laser - GMAW - tandem GMAW process (FRONIUS, 2008c)

Stauffer (2007) mentions another hybrid approach for Laser and tandem GMAW. In this version a tandem GMAW torch is placed trailing the Laser beam (Figure 2.50). The leading Laser beam is used for welding the root of joints, and the trailing tandem process used for increasing the ability to bridge the gaps and throat thickness. It has been claimed that this process is able to increase not only the welding speed, but also the ability to bridge root gaps compared to the conventional Laser - single GMAW.

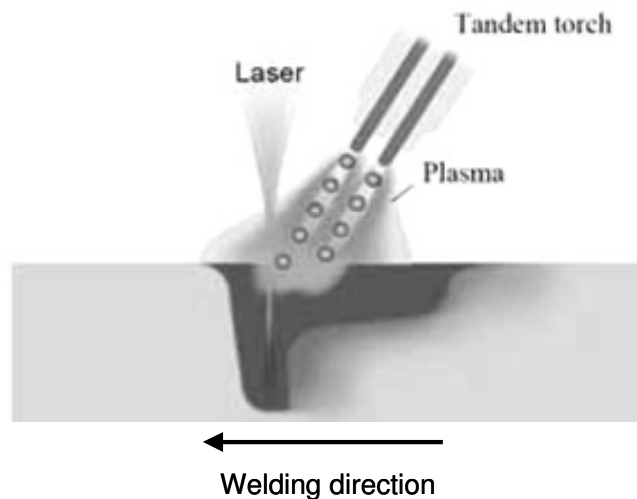


Figure 2.50: Schematic illustration of the Laser - tandem GMAW process (STAUFER, 2007)

2.4 Magnetic Fields versus Welding Arcs

Problems of arc interruption have been noticed during tandem pulsed GMAW by Ueyama et al. (2005). A hypothesis for such phenomenon seems to be linked to the magnetic field generated by the arcs and their stiffness. As a result of these magnetic fields, forces are generated and the arcs are more or less deflected depending on their stiffness. In the case of the trailing arc, the force seems to be strong enough to blow it out. The arc would

be deflected at such a level that it lost its root (connection) with the workpiece. For some reason the problem seems to be concentrated in the trailing wire.

Despite this possible related problem, magnetic fields can be also used in welding in a positive and useful way. The welding arc self-induced magnetic field is the basis for plasma jet formation, which has effects on weld bead penetration, for instance. In addition to this fact, external magnetic fields have been used to oscillate welding arcs, replacing mechanical devices in coating applications, for instance. Marques (1984) built a device for this purpose and mentioned that the arc could be destabilised if the magnetic field produced was too intense. Figure 2.51 illustrates the device devised by Marques. The idea of using an alternated/external magnetic field to oscillate welding arcs was patented in the 60's by Greene (1960). Figure 2.52 shows an illustration of the device developed by Greene. Nowadays there are even commercial equipments available (Figure 2.53). Controlled AC power supplies are used to control/oscillate the arcs.

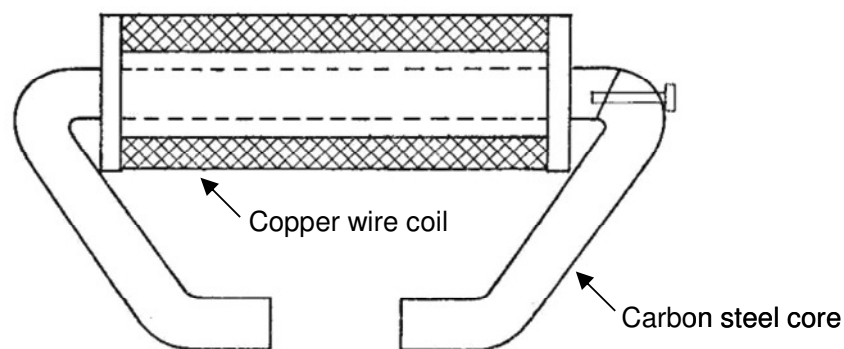


Figure 2.51: Device devised by Marques (1984) for magnetic arc oscillation

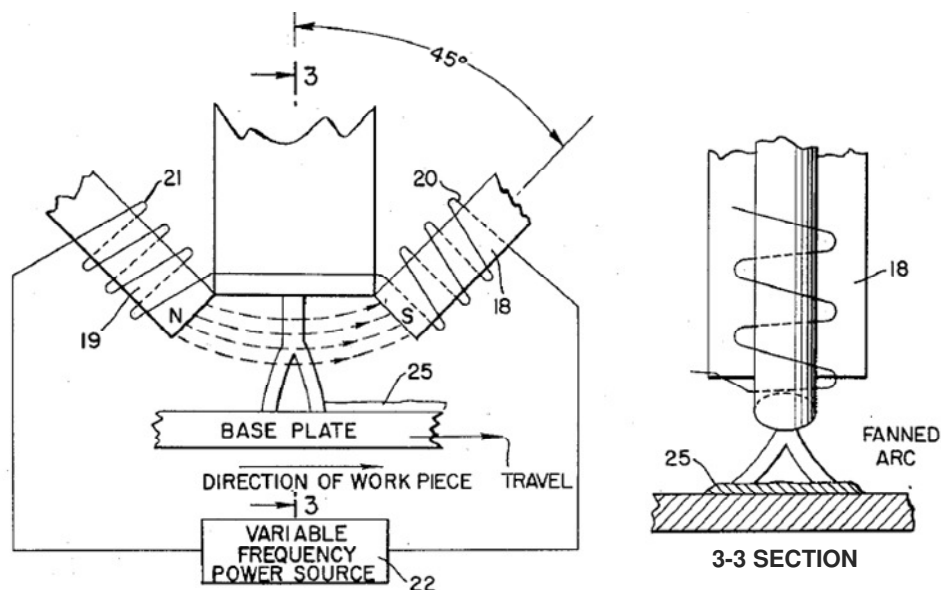


Figure 2.52: Diagrammatic illustration of magnetic arc oscillator patented by Greene (1960)

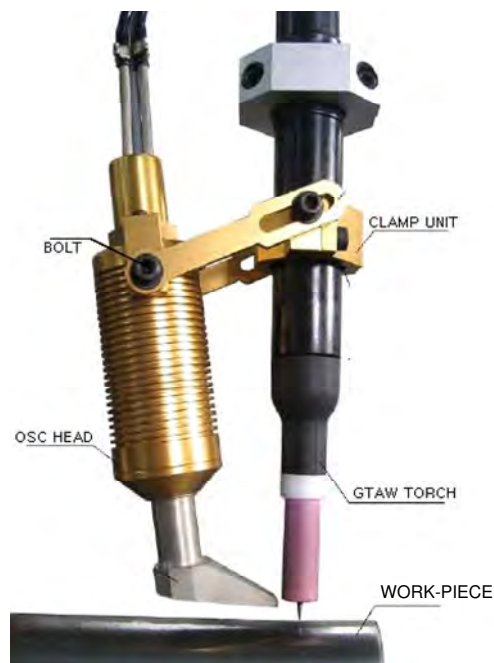


Figure 2.53: Example of commercial equipment that uses magnetic field to oscillate welding arcs (HANGIL, 2009)

Figure 2.54 shows different concepts for magnetic oscillators. Item (a) shows a single-tip, water-cooled probe that adapts to conventional torches. According to the manufacturer (AP AUTOMATION, 2009), this device is indicated for tight clearances and is primarily used to weave the arc across the seam or to stabilize the arc. Item (b) shows a dual-tip probe used in conventional GTAW torches for cross-seam weaving or in-line weaving. At last, item (c) shows a probe with four independently controlled magnetic coils. As illustrated in Figure 2.55, this kind of device allows multiple arc profiles to be produced. It requires, however, a more complex control unit.

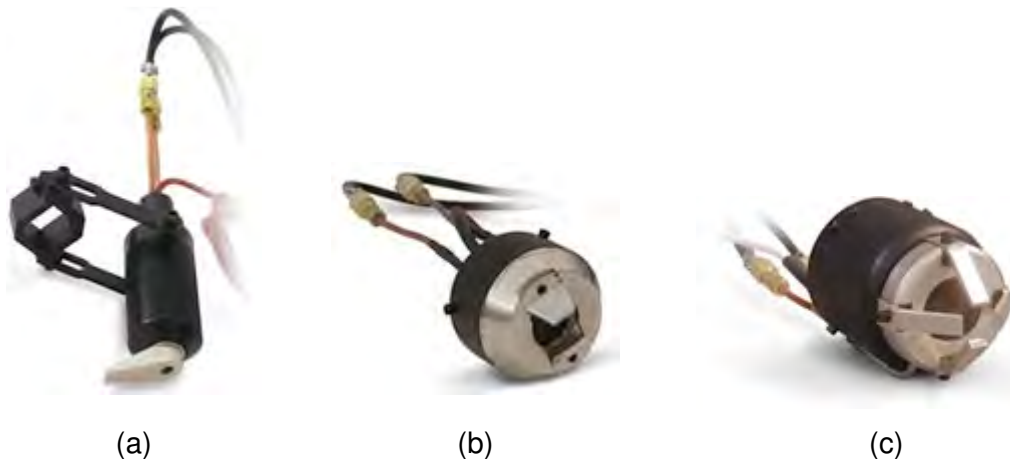


Figure 2.54: Different configurations for magnetic oscillators (AP AUTOMATION, 2009)

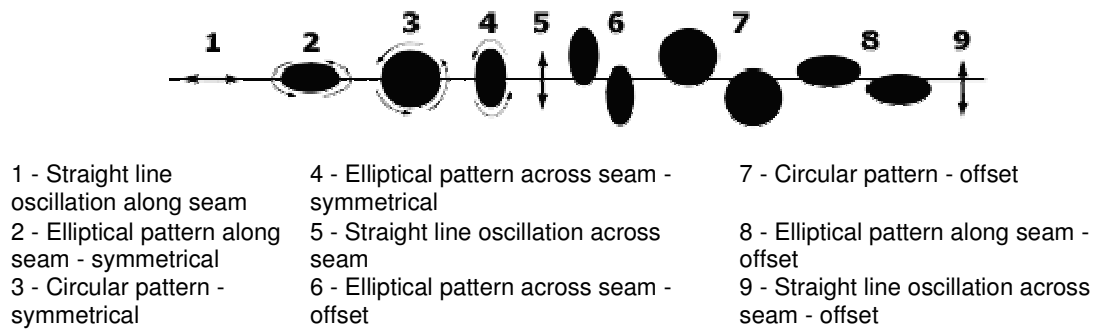


Figure 2.55: Multiple arc profiles obtained by using the oscillator (C) of Figure 2.54
(AP AUTOMATION, 2009)

CHAPTER III

EQUIPMENTS AND RESOURCES

This chapter describes the equipments and resources developed and/or used essentially during the assessment of the tandem GMAW approaches. Exceptions and complements are mentioned along the way in the respective chapter or section.

3.1 Welding Table

In order to verify the accuracy of the travel speed of the welding table to be used in the welding trials, a travel speed calibration was carried out. Figure 3.1 shows the welding table and the control (weld start and stop, speed and direction control) used to set the travel speed. As can be seen, the tandem torch is fixed and the table moves (as the arc stays in the same position, high-speed filming can be accomplished easily).

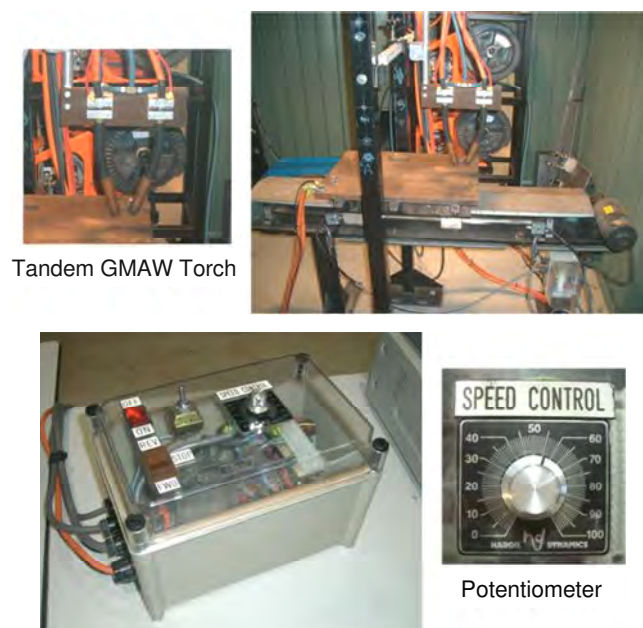


Figure 3.1: Welding table (above) and control (below) used with the GMAW tandem torch

3.1.1 Travel speed calibration

The travel speed calibration was carried out using a stop-watch and references on the welding table for a right-to-left movement. As a means of verifying the accuracy of the welding table movement in the opposite direction, some measurements were also taken for the left-to-right direction of travel.

The summarized results for the travel speed calibration are shown in Figure 3.2. Further details are given in extra tables in Appendix 2. The minimum value of travel speed provided by the welding table is approximately 90 mm/min and the maximum value is around 1620 mm/min. The values of travel speed for the left-to-right motion are very similar to those when the table is moved from right to left, meaning that the calibration equation showed in Figure 3.2 can be used for both directions of movement. The standard deviations shown in Appendix 2 indicate the consistence (repeatability) of the welding table motion.

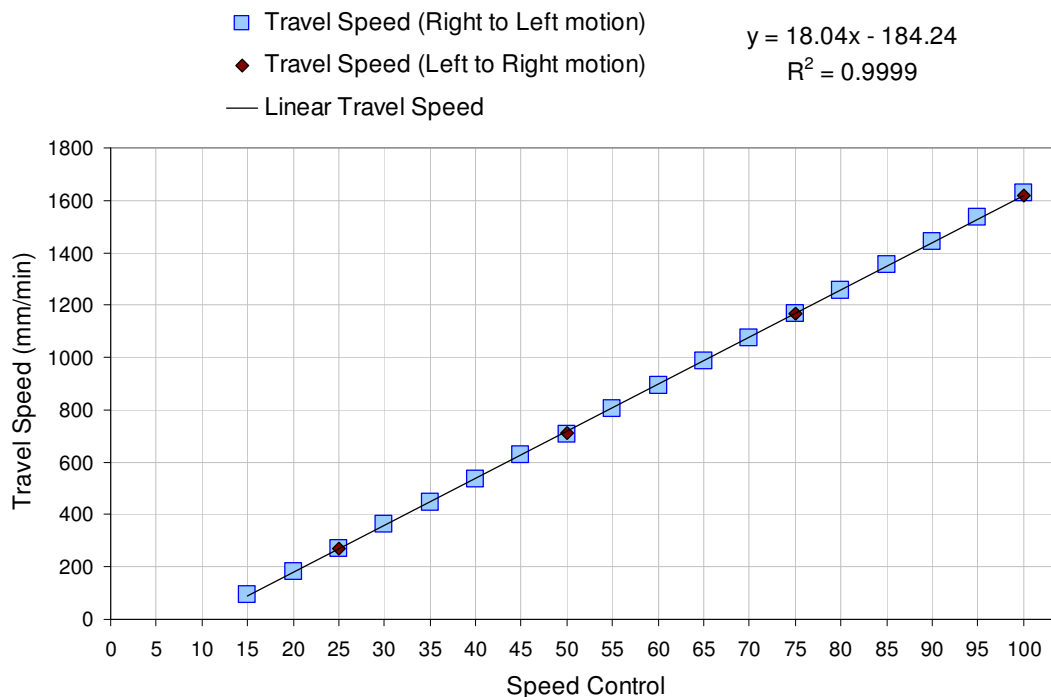


Figure 3.2: Travel speed calibration curve and equation

3.2 Tandem GMAW Torch

Figure 3.3 shows the tandem GMAW torch previously built at University of Wollongong by Cuiuri and Norrish (2006). This tandem torch was built to allow flexibility for the positioning (angle) of the electrodes (more setting freedom than commercial torches). So the bodies of the torch were made flexible and adjustable. But as the consistence of positioning has

extreme importance in tandem GMAW welding, a device was designed to assure the position of each electrode (torch bodies angle) and to maintain them in that position throughout the trials. The second, but not least import, aim of this device was to provide the same alignment for both electrodes. The alignment along the direction of welding assure that both electrodes are in the same joint track, with the added material provided by the trailing wire going straight on top of the material provided by the leading wire. Figure 3.4 shows the alignment device and Figure 3.5 presents such device assembled in the tandem GMAW torch.

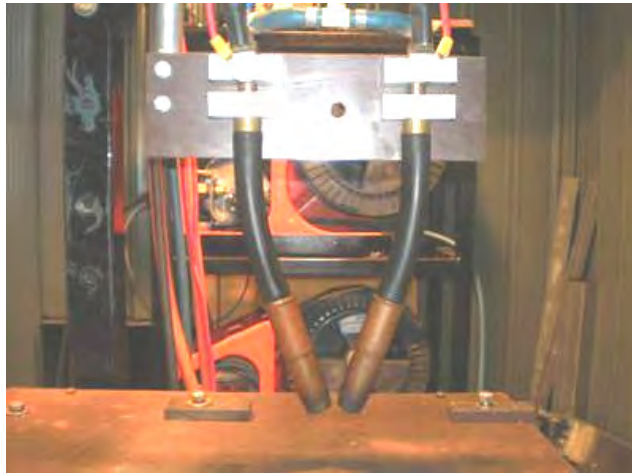


Figure 3.3: Tandem GMAW torch designed at University of Wollongong

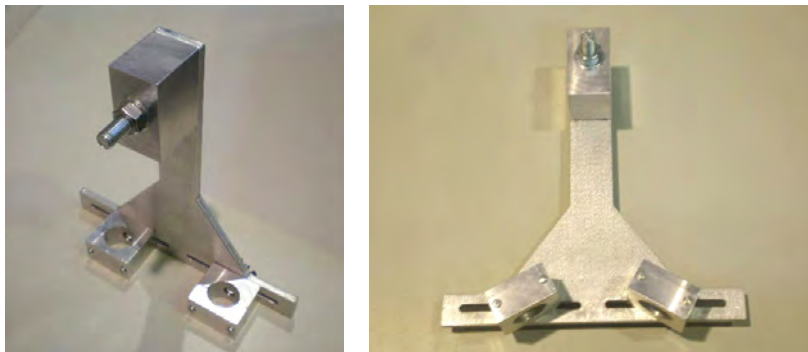


Figure 3.4: Aligement device designed to improve the tandem GMAW torch

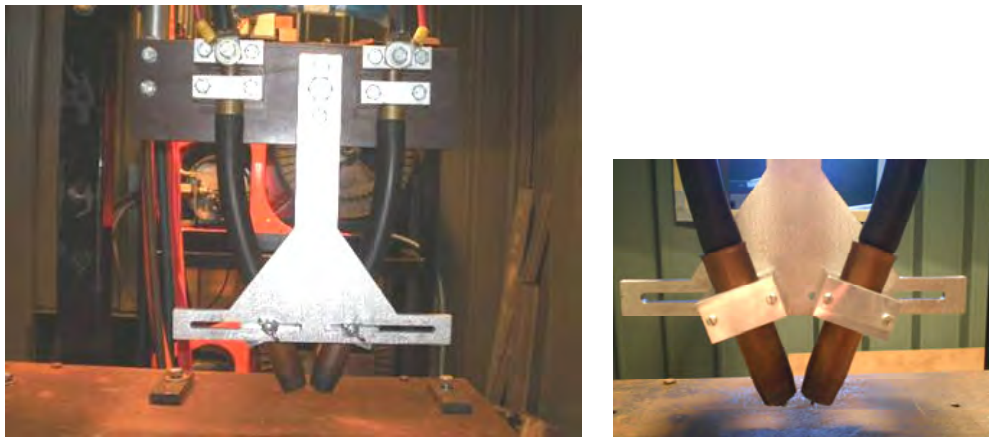


Figure 3.5: Aligement device assembled in the tandem GMAW torch (back view on the right)

As a means of improving the CTWD (contact to workpiece distance) setting, a linear gear was assembled in the welding rig to allow vertical up and down movements of the welding torch (Figure 3.6). Through the new device the distance between the contact tip and the workpiece can be set quickly without any interference in the torch angle and alignment.

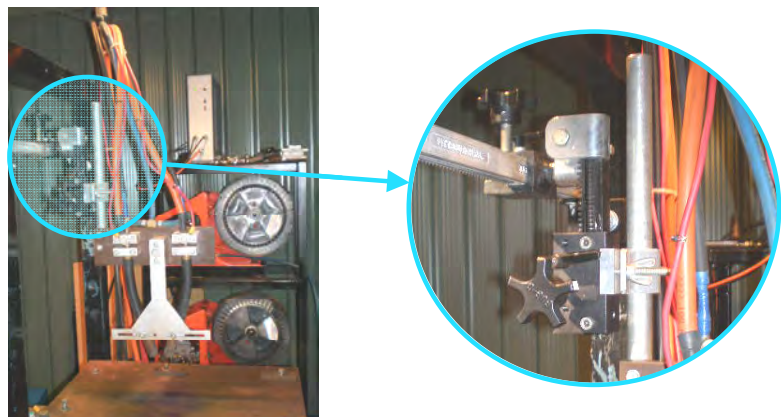


Figure 3.6: Apparatus for CTWD setting for the tandem GMAW torch

With the purpose of assuring the angle between the electrodes to remain constant when the inter-wire distance is changed, the welding torch was modified once more (Figure 3.7). The first wire was allowed to move forwards and backwards through two slots made in the torch body.

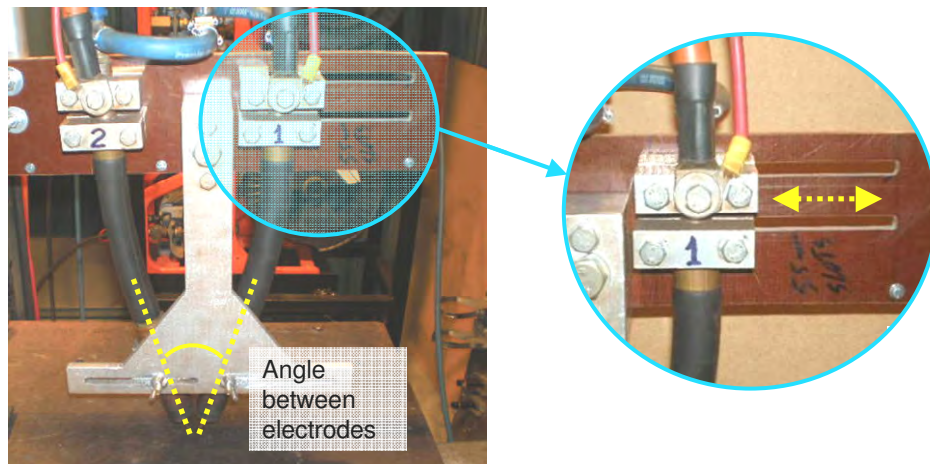


Figure 3.7: Details of slots (on the right) made in the welding torch

3.3 Backlight Sources and Data-Image Synchronisation and Analysis

3.3.1 Backlight sources

High-speed filming has become an important tool for welding research and development. However, a reasonable quality of the welding process images is required to allow a better understanding of the phenomena involved and to facilitate any necessary developments in the welding process control. In order to have reasonably clear images of the welding process (electrical arc, droplets being transferred and molten metal pool), backlighting is necessary to be used with the high-speed camera available. A range of approaches using simple commercial tungsten halogen lamps (500 W and 2 kW spot lights) and a commercial focused beam light (stage light) were tried. All the images shown in this section were recorded using the high-speed camera available at the welding laboratory of the University of Wollongong. The camera (RedLake Motion Pro X3 Plus model) was used with a lens Nikon Micro AF and all videos (images) were recorded at 5,000 frames per second.

Considering the results achieved throughout the search for an adequate backlight, four filaments of 1 kW each were used and aligned to provide a “net” of light (Figure 3.8). Figure 3.9 shows the new lamp already built. As a means of improving the image quality, the gamma and saturation settings available in the software of the camera were changed. The software available for the camera allows to change the settings of the images while they are still in the camera memory (the desired setting is chosen by the user and the images can be saved with the correction). Figure 3.10 shows the image with the gamma and saturation corrections already applied.

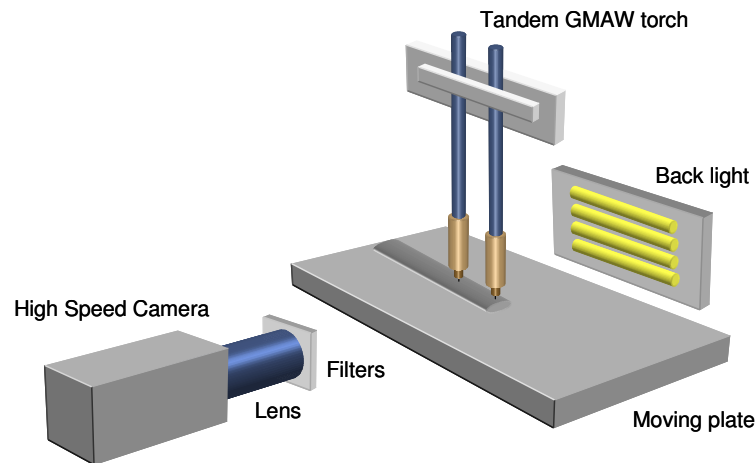


Figure 3.8: Idea of a “net” of light in the background



Figure 3.9: Lamp built using 4 halogen bulbs of 1 kW each (the filaments were placed in such a way to provide a net of light)



Figure 3.10: Image using 4 halogens bulbs of 1 kW each (as the tungsten filaments were placed to form a big “net” of light, all background was illuminated) (Camera exposure time: 97 μ s; Lens aperture: 4; Filter: neutral density COKIN P153 grey and red COKIN P3; Correction: gamma 3.5 and saturation 0)

The lamp design was then fitted with a fan (to cool down the bulbs and increase their service lives), a front glass (Pyrex to resist the heat) and a top cover, both of them to avoid spatters from reaching the bulbs and for safety reasons. Figure 3.11 shows the lamp at its

final stage. This lamp represents also an economical solution, since the price of each bulb was around US \$ 10.00 and their life span is estimated in more than 2,000 hours.



Figure 3.11: Final lamp using 4 halogen bulbs of 1 kW each

3.3.2 Data-image synchronisation and analysis

A system for synchronisation of high-speed video images and transient electrical data was devised (Figure 3.12). A data acquisition program developed using National Instruments LabVIEW™ allows the selection of the data acquisition rate (typically 5000 Hz) and acquisition time (nominally 0.125 s). Both parameters must be coincident with the values set in the high-speed camera to assure synchronisation. When the data acquisition begins, the program synchronises (starts) the image acquisition in the camera using a single digital pulse sent to the camera trigger input. After acquisition, the synchronised images and electrical transient data can be displayed and analysed using another software tool developed as part of this work. This tool was built using National Instruments DIAdem™ (Figure 3.13). This software tool allows the user to correlate events in the transient electrical signals with visibly observable phenomenon. This synchronisation method was successfully demonstrated using tandem pulsed GMAW and short-circuit GMAW, where the pulses and short-circuit moments, respectively, were used as references to verify the synchronisation.

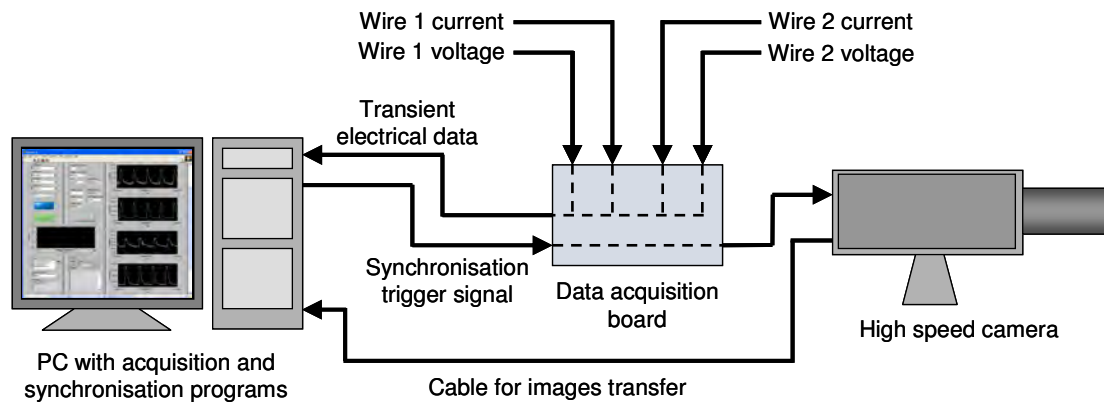


Figure 3.12: System for synchronisation of high-speed video images and transient electrical data

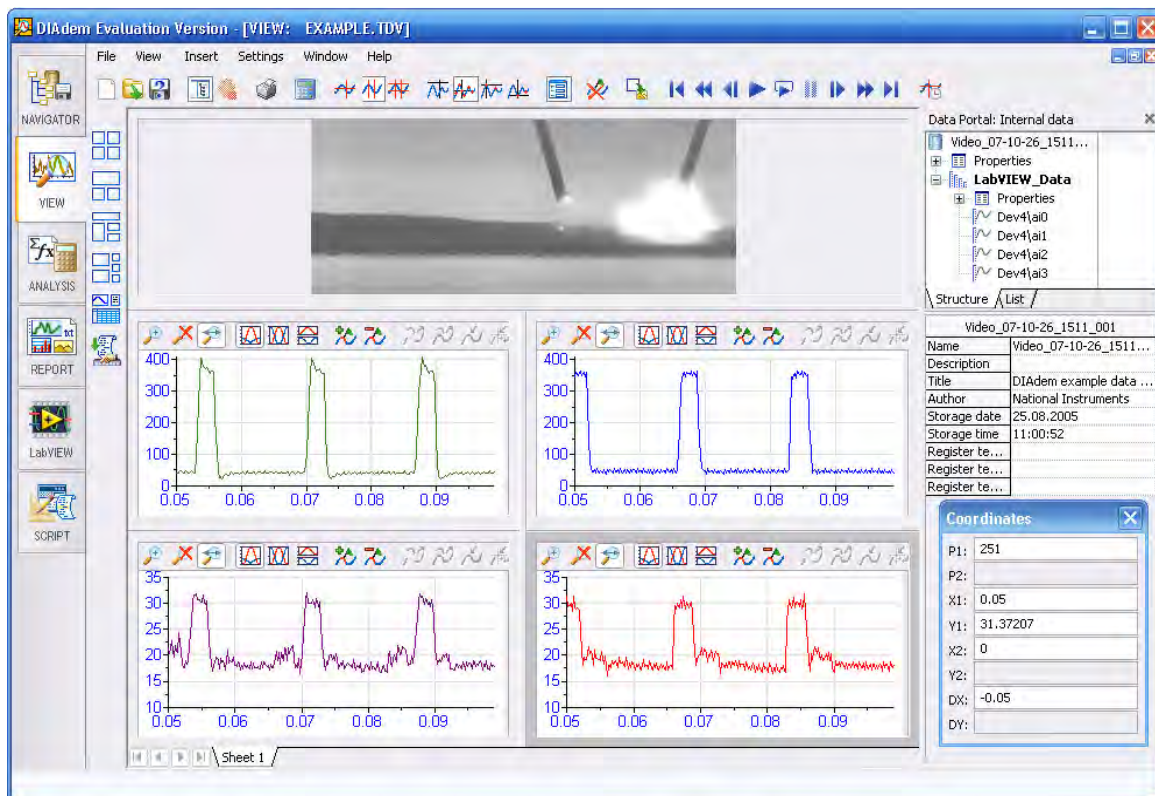


Figure 3.13: Screenshot of software tool built for welding process analyses

3.4 Extra Information

3.4.1 Data acquisition

As the electrical interfaces (Figure 4.1) used in the welding control system described in the next chapter were previously calibrated to provide the right wire feed rate and the right welding current and voltage, a calibration for this variables was unnecessary. The acquisition

process was, then, carried out by taking the electrical signals from feedback connections (Figure 4.2) at the interfaces (signals coming from the welding process already attenuated). A National Instruments acquisition board and a personal computer hosting a LabVIEW™ program for acquisition of four channels were used. These channels were used throughout this work for welding currents and voltages. The wire feed rate signal was not acquired.

3.4.2 Power sources

Figure 3.14 shows the power sources used during the assessment of the tandem GMAW approaches: a Thermal Arc 600GMS model (up to 600 A) and a Thermal Arc Power Master 500 model (up to 560 A). Both power sources are capable of multiple process operation, but, since they were controlled externally, they were set to SMAW.



Figure 3.14: Power sources used for the tandem GMAW applications

3.4.3 Electrodes and gases

During the assessment of the tandem GMAW approaches, an AWS ER 70S-6 wire with nominally 1.2 mm in diameter was used. Concerning the shielding gases used for these assessments, 98.5% Ar plus 1.5% O₂ was used for the pulsed operation mode and 81.25% Ar plus 16% CO₂ plus 2.75% O₂ was used for the short-circuit mode. Regardless of the shielding gas used, the total flow was kept at 35 l/min (total gas flow in the leading and trailing part of the tandem torch).

CHAPTER IV

STUDY ON CURRENT WAVEFORM CONTROL

4.1 Tandem GMAW with Pulsed Current Waveform

As a means of giving more flexibility to the trials using the tandem GMAW process, a tandem GMAW program (FlexTandem - Pulsed 1) was built based on previous programs utilized at University of Wollongong. The new program was built also in order to offer a more amicable user interface, allowing all the parameters to be seen in the same screen and “one click” parameters setting.

4.1.1 Controller

The control system must have the ability to operate two power sources simultaneously and allow a large number of parameters to be set for each wire in order to vary the welding current waveform differently for each wire. The control must also have a short response time (execution time) to successfully control the welding process.

The welding controller used is based on a DSP (digital signal processor) board that is installed into a desktop computer (PC). The processor has a 32 bit floating point core capable of 50 MFLOPS (million floating point operations per second). Hardware on the board is configured to generate an interrupt every 40 μ s (25 kHz), and this feature is used as the basis for repeated execution of the control program. Once initiated, the execution is independent of the host PC's operating system. Other functions, such as data transfer to the PC and auxiliary “background” calculations, are performed in the free time between servicing the process control program interrupts. The control program (DSP) is programmed in C high level language. An appropriate compiler is used to produce the downloaded executable file. The controller function is adaptable to different welding processes (including GMAW) and different equipment that may be fitted to the welding test facility. Figure 4.1 shows the

controller host PC, the electrical interfaces (responsible for filtering and conditioning the voltage signals from the power sources), and other equipment associated. Figure 4.2 presents the test facility diagram for tandem GMAW.

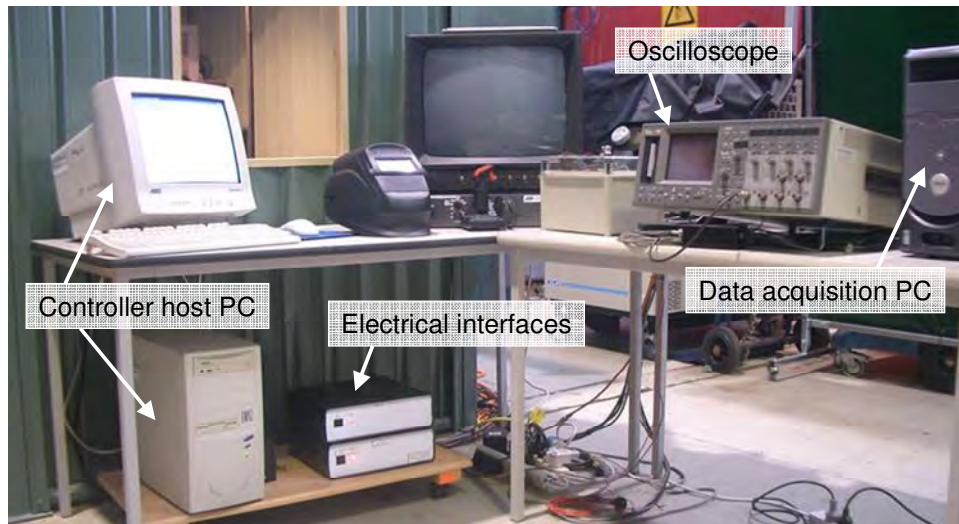


Figure 4.1: Controller host PC and electrical interfaces used (CUIURI; NORRISH, 2006)

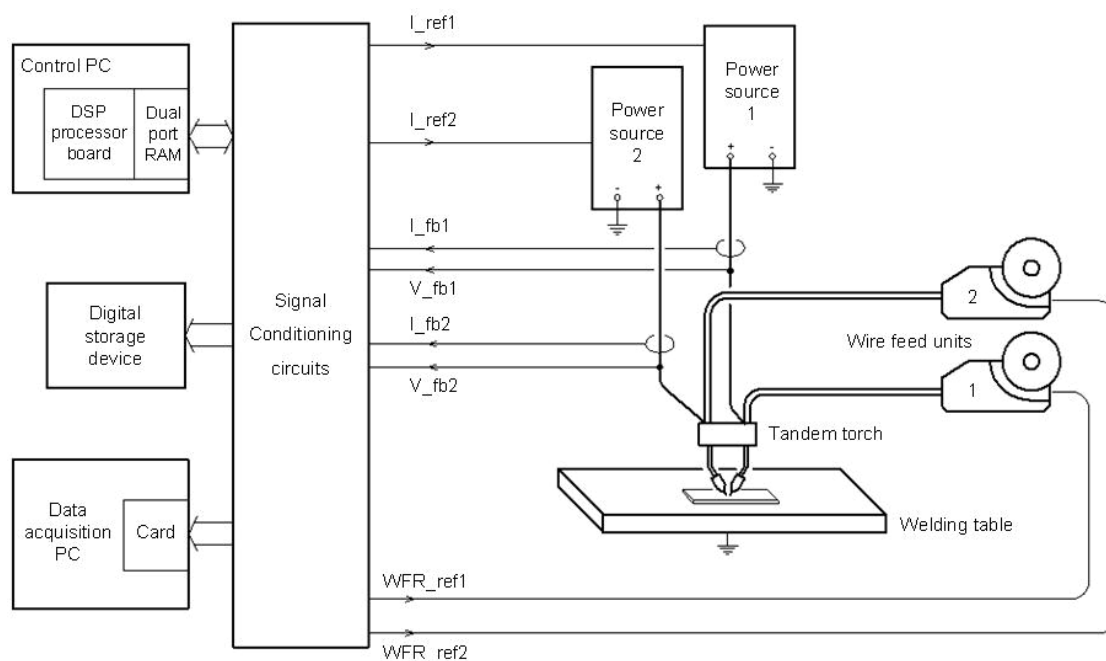


Figure 4.2: Test facility diagram for tandem GMAW

4.1.2 Description

Figure 4.3 illustrates the generic current waveforms (wire 1 and wire 2) generated by the FlexTandem (version Pulsed 1) program with the main parameters indicated. Tables 4.1, 4.2 and 4.3 list all parameters that can be set in the version Pulsed 1 of the FlexTandem program and present a summarized description of their purpose. Figure 4.4 shows the FlexTandem (version Pulsed 1) state diagram.

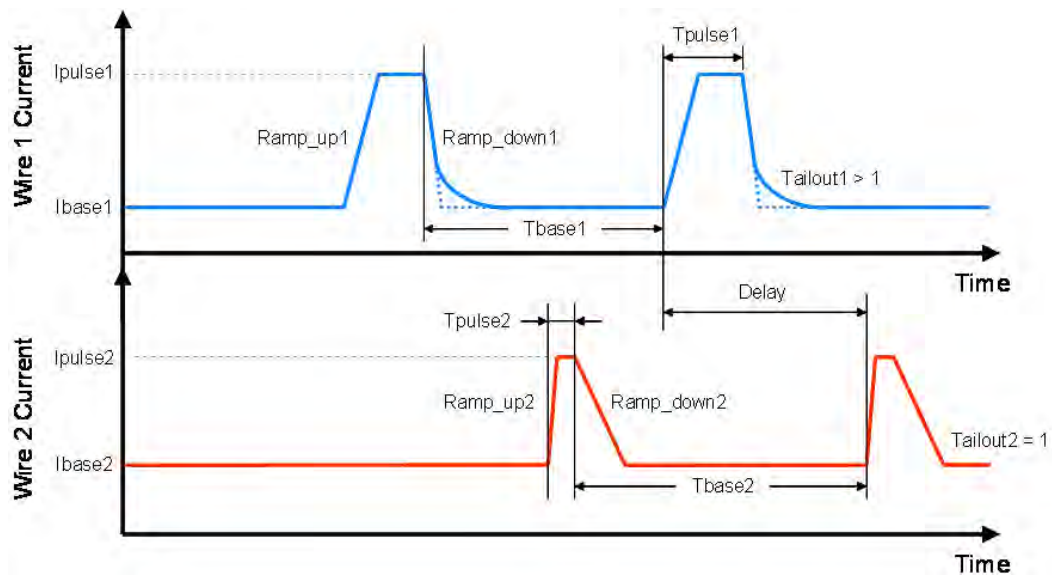


Figure 4.3: Scheme of generic current waveforms generated by the FlexTandem (version Pulsed 1) program with the main parameters indicated

Table 4.1: List of parameters for wire 1 in FlexTandem - Pulsed 1

Parameter [units]	Summarized description and/or purpose
Welding parameters	
Ipulse1 [A]	Pulse current setting for wire 1
Tpulse1 [s]	Time that wire 1 operates in the pulse current level
Ibase1 [A]	Base current setting for wire 1
Tbase1 [s]	Time that wire 1 operates in the base current level
Ramp_up1 [A/ms]	Rate that the current in the wire 1 goes from the base to the pulse level
Ramp_down1 [A/ms]	Rate that the current in the wire 1 goes from the pulse to the base level
Tailout1 [dimensionless]	Factor that controls the current waveform during the ramp down in wire 1
WFR1 [m/min]	Feeding rate for wire 1
Arc voltage control parameters	
AVC_Ref1 [V]	Arc voltage control reference for wire 1
AVC_Gain1 [A/V]	Arc voltage control proportional gain for wire 1
AVC_Range1 [A]	Arc voltage control adjustment range for wire 1

Table 4.2: List of parameters for wire 2 in FlexTandem - Pulsed 1

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

* Tbase2 is dictated by Tpulse1, Tbase1 and Tpulse2 in order to keep the pulsing synchronization between wires.

Table 4.3: List of parameters common to both wires in FlexTandem - Pulsed 1

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
General parameters	
Delay [ms]	Time-shifting between the pulses of wire 1 and 2
WFR_creep [m/min]	Creep wire feed rate

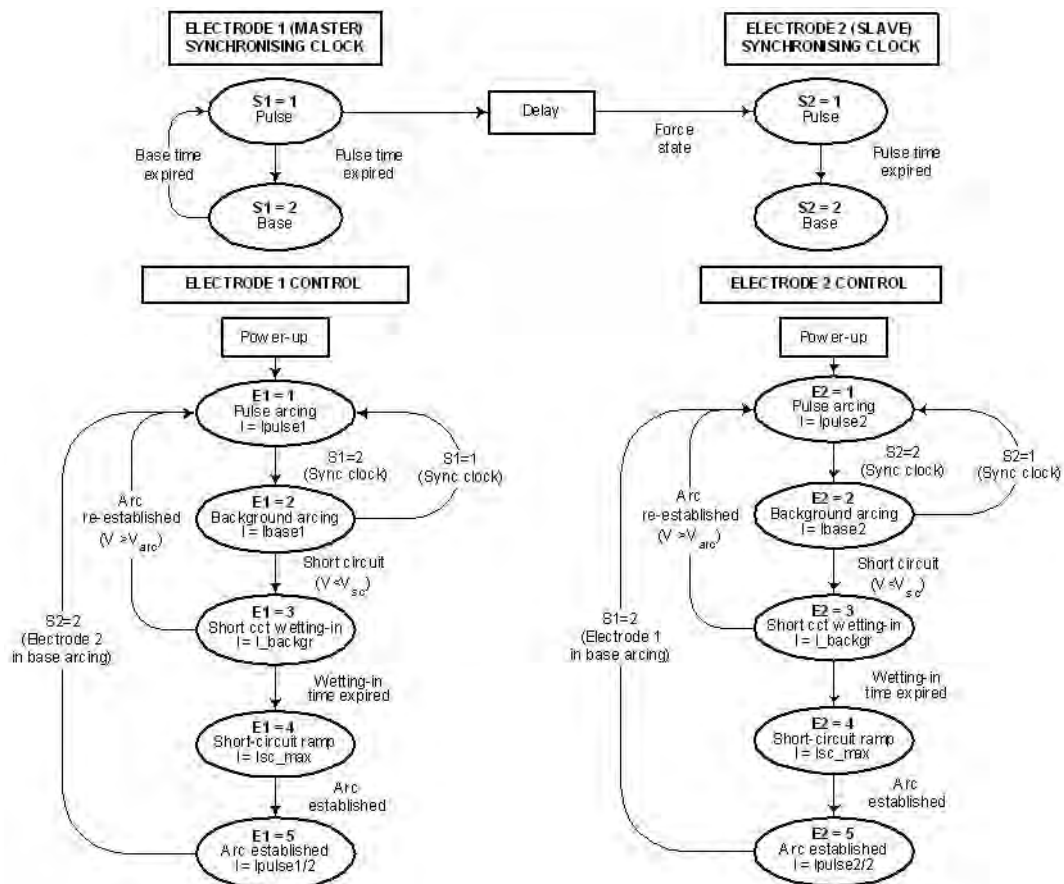


Figure 4.4: Program state diagram for FlexTandem - Pulsed 1

The program user interface was built using Borland C++Builder3. This interface is a medium through which welding parameters are transferred to the DSP controller and it is also used to display the process data and program status. Figure 4.5 shows the FlexTandem interface screen (Version Pulsed 1). Besides of having amicable user interface (all parameters can be seen in one screen only, the parameters setting is facilitated, etc.), this program allows setting different parameters for wire 1 and 2 (important as two different power sources are employed) and the delay between the current pulses of wire 1 and 2 can be set. These features give this program more flexibility to investigate the applicability of tandem pulsed GMAW.

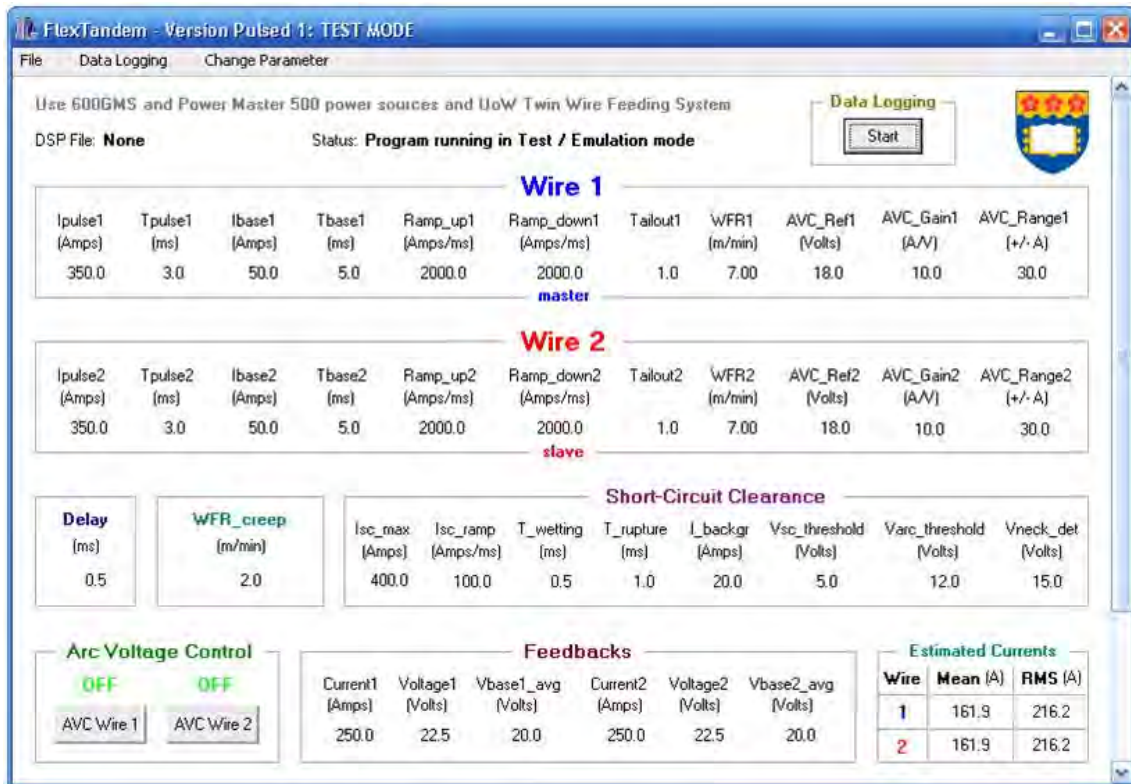


Figure 4.5: FlexTandem program screen (version Pulsed 1)

As shown in Figure 4.6, the FlexTandem - Pulsed 1 program presents three menus on the top of its interface screen (File, Data Logging and Change Parameter), and also shows the current DSP file used and program status. By selecting the File menu, some options are offered to the user (Figure 4.7). It is possible to download the DSP executable file (.out file), which is generated by the FlexTandem DSP program and is responsible for the communication and operations between the computer (interface) and the two power sources and wire feeders. It is also possible to have all the parameters saved and downloaded in order to facilitate analysis and possible trials replica (an example of parameters file is showed in Appendix 3). Further more, the File menu allows the user to save logged data (all parameters settings and instant values for current and voltage for each wire, besides some others details).

Program download and data exchange is performed through dual port RAM, a shared area of memory that is accessed by both processors. Low level arbitration is transparently performed by the hardware. An additional level of software arbitration is incorporated into both PC and DSP programs, to ensure that consecutive transfers of data always contain fresh data.

The data logging characteristics are defined in the Data Logging menu. As shown in Figure 4.8, the sampling time (40 to 1000 μ s) or the logging time (up to 1.5 s) can be defined

through this menu (the number of samples is fixed in 1500) and the data logging can be started (an equivalent function is featured by the Data Logging button (Figure 4.5)). The data logging feature is not intended to replace the data acquisition needed in welding research, which must be performed by a separate dedicated system with greater storage capacity. Instead, the data logging is used as a fault-finding or debugging tool for process development. An example of data logging file is showed in Appendix 3. This program has the advantage of access to all data within the DSP controller, not just the basic external signals.



Figure 4.6: Pull-down menu and status information in FlexTandem - Pulsed 1

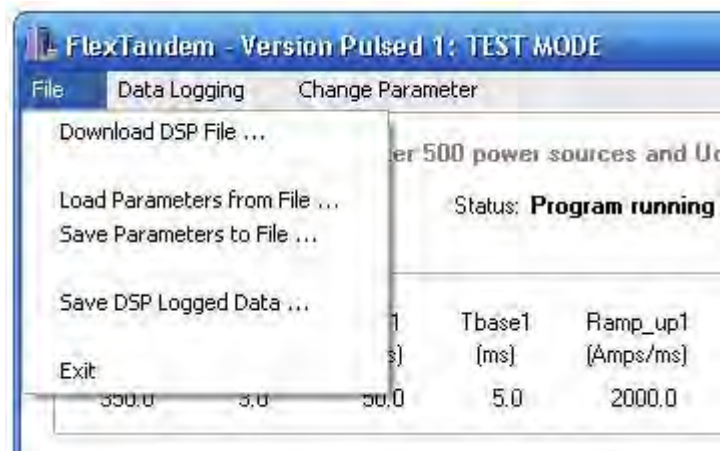


Figure 4.7: File menu options in the FlexTandem - Pulsed 1

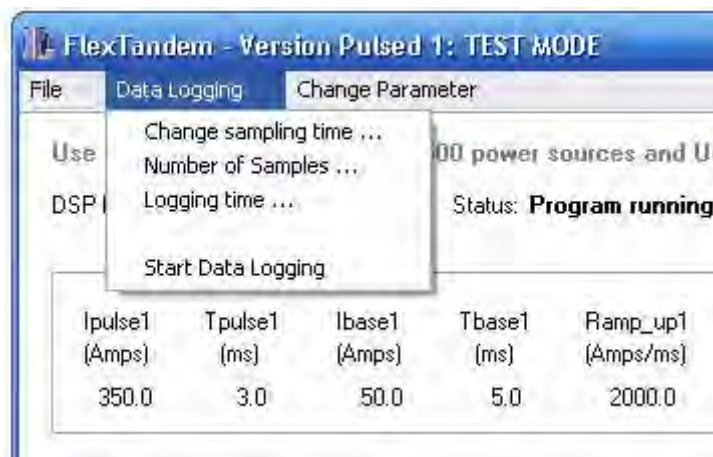


Figure 4.8: Data Logging menu options in the FlexTandem - Pulsed 1

The third menu, called Change Parameter, gives the user the possibility of setting all the welding parameters for each wire accessing the kind of parameter to be changed (Figure 4.9). Parameters are changed as required through pull-down menus and dialog boxes. Figure 4.10 gives an example of how a welding parameter is set. All these parameters can be set using the Change Parameter menu (where a short explanation of each parameter is given) or simple by clicking on the name of the parameter on the screen. Both methods come up with the Change Control Variable box (Figure 4.10 b) related to the parameter selected.

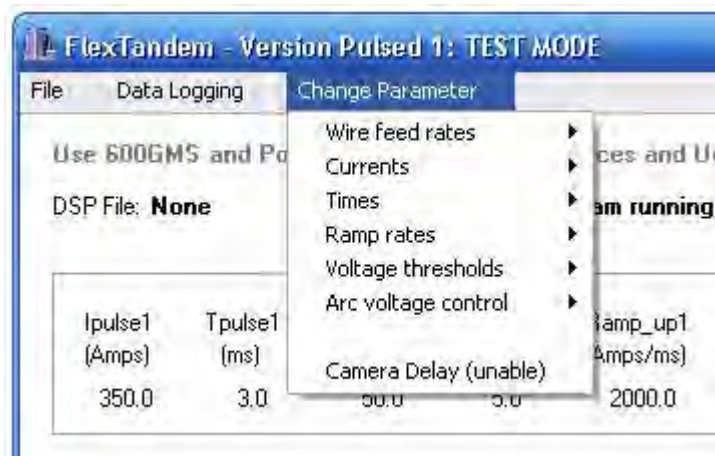
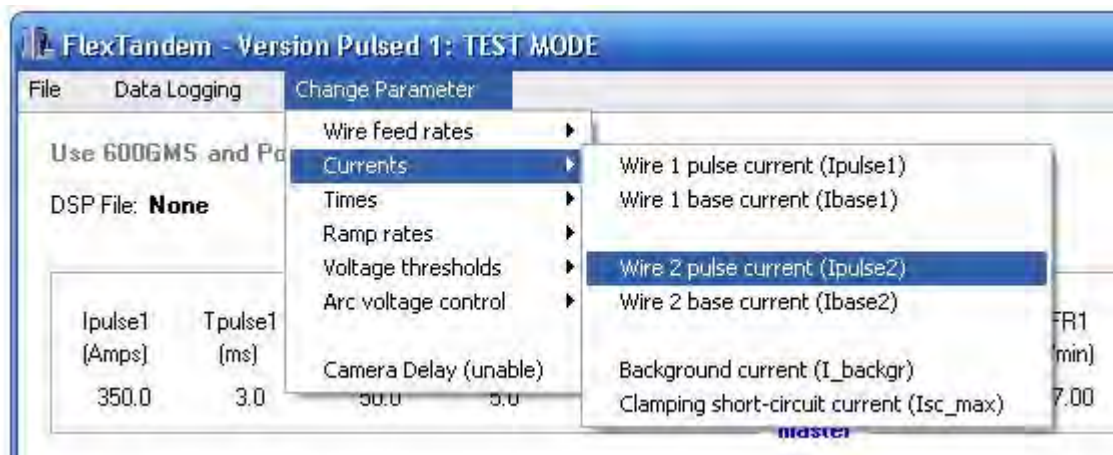
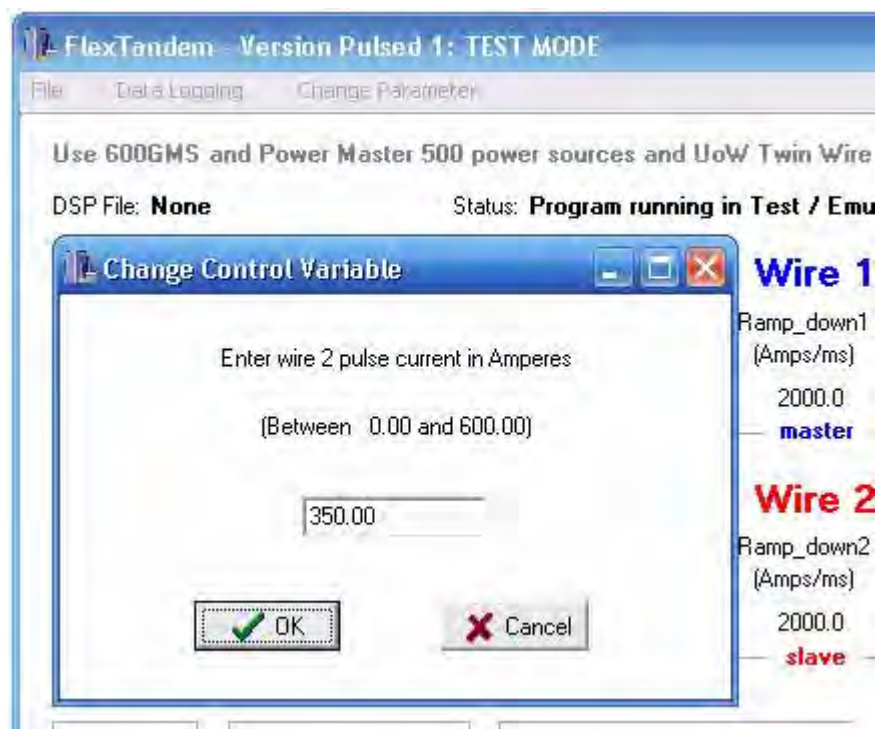


Figure 4.9: Change Parameter menu options in the FlexTandem - Pulsed 1



a) Selecting a welding parameter



b) Setting a new value for the welding parameter selected

Figure 4.10: Setting a welding parameter in the FlexTandem - Pulsed 1

In order to keep the current pulses of the wires synchronised, the Tbase2 (time in which the wire 2 remains in the base current level) cannot be set. Instead, the Tbase2 value is dictated by Tpulse1, Tbase1 and Tpulse2. The resultant Tbase2 value is shown automatically on the screen and a message box is presented to the user if the change of this parameter is tried (Figure 4.11).



Figure 4.11: Tbase2 Message box in the FlexTandem - Pulsed 1

Short-circuit clearance

Despite the FlexTandem (version Pulsed 1) program was built to operate both wires in pulsed welding mode, complications come up if one electrode enters in short circuiting while the other is in open-arc mode. This sort of event can occur either at the weld start, or during the weld (caused by a reduction in CTWD, for instance). In such case, a short-circuit clearance procedure is applied placing priority on not disturbing the open-arc electrode (stable condition). The short-circuit clearance parameters are common to both wires (electrodes), as they just add more stability to the process (secondary parameters). In order to avoid (or minimize) instabilities, a specific waveform is applied to the current if a short circuit is detected (Figure 4.12). The large current pulse that is usually applied to the electrode in short circuiting as a rupture occurs is delayed if the open-arc electrode is in the pulsing period. Once the pulsing period of the open-arc electrode expires, a pulse of current is applied to the electrode that is emerging from the short-circuit condition, increasing the arc length and establishing a stable open-arc condition. Figure 4.13 shows the short-circuit clearance control parameters, which set the short-circuit waveform in the FlexTandem program. This control method is able to produce rapid and reliable arc starting, and recovers well from disturbances during the welding operation (CUIURI; NORRISH, 2006).

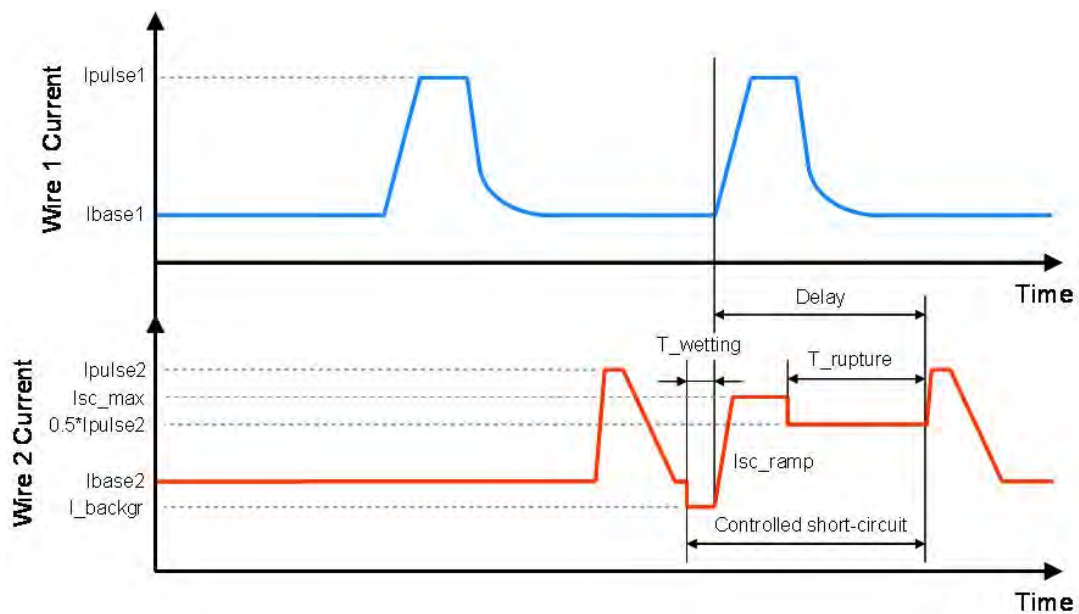


Figure 4.12: Scheme of generic current waveforms generated by the FlexTandem - Pulsed 1 with a short-circuit clearance in wire 2

Short-Circuit Clearance							
Isc_max (Amps)	Isc_ramp (Amps/ms)	T_wetting (ms)	T_rupture (ms)	I_basegr (Amps)	Vsc_threshold (Volts)	Varc_threshold (Volts)	Vneck_det (Volts)
350.0	150.0	0.5	1.0	20.0	8.0	18.0	20.0

Figure 4.13: Short-circuit Clearance control in the FlexTandem - Pulsed 1

Arc Voltage Control

The FlexTandem program was built with the possibility of operating with an arc voltage control (AVC) system. The AVC option featured in the FlexTandem program allows the user to select between operating in conventional pulsed GMAW, when the AVC button is OFF, or using an “external” control to keep the arc length constant. As magnetic interaction between the arcs tends to be minimized (or controlled) by introducing a preset time delay between the pulses of current of the two electrodes (Delay parameter), the pulsing frequency for both electrodes is required to be the same to keep the synchronisation. So the arc length control for each wire has to be performed by adjusting the base current (Ibase), rather than adjusting the base time (Tbase). By setting the AVC button ON, a routine in the FlexTandem program (DSP file) tunes the base current value automatically within a selected range (AVC_Range) to perform the arc length control. The AVC control is based on a comparison between the average voltage value (Vbase_avg) (based on voltage values sampled at 25 kHz) taken

during the final half of the base time (T_{base}) (due to possible tail-out presence) and the AVC_Ref parameter. Actually, the V_{base_avg} is calculated based on the last four base times and the amount the I_{base} value is changed (the arc length is changed) is defined by the difference between those voltage values times the AVC_Gain (Amper per Volts). The AVC is always actuating on base current based on the last four base times. The AVC option can be activated separately for each wire (Figure 4.14) and works based on parameters set for each wire (Figure 4.15). With this approach, control of the arc length is relatively straightforward, provided that both electrodes operate in open-arc conditions (CUIURI; NORRISH, 2006).

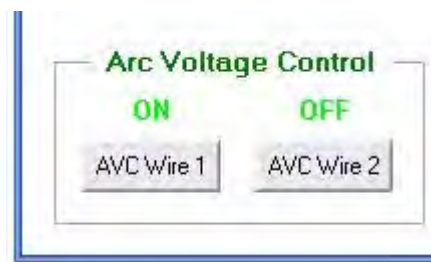


Figure 4.14: Arc Voltage Control option in the FlexTandem - Pulsed 1

AVC_Ref1 [Volts]	AVC_Gain1 [A/V]	AVC_Range1 (+/- A)
35.0	25.0	50.0

AVC_Ref2 [Volts]	AVC_Gain2 [A/V]	AVC_Range2 (+/- A)
35.0	25.0	50.0

Figure 4.15: AVC parameters for each wire in the FlexTandem - Pulsed 1

Electrical feedbacks

In order to allow the user to carry out a real time checking of the current and voltage values, a group of feedback values is provided in the FlexTandem program. It is possible to check the instantaneous values of current and voltage for both wires and the averages of the voltages when the arcs are in the base current (provided to help in any possible fault detection of the Arc Voltage Control feature). The feedback values (Figure 4.16) can be saved in the DSP Logged Data (option in the File menu) to allow detailed analysis.

Feedbacks					
Current1 (Amps)	Voltage1 (Volts)	Vbase1_avg (Volts)	Current2 (Amps)	Voltage2 (Volts)	Vbase2_avg (Volts)
250.0	22.5	20.0	250.0	22.5	20.0

Figure 4.16: Feedbacks values provided by the FlexTandem - Pulsed 1

Estimated currents

The Flex Tandem program also features a field where an estimative for the currents (mean and RMS values) of both wires is presented to the user (Figure 4.17). These estimated currents are calculated based on the values (waveform parameters) set in the screen and give an idea about the current levels to be expected from the welding process. This feature may be a useful tool when the user wants to change the pulse parameters keeping the mean and/or RMS currents at a desired level, for instance.

Estimated Currents		
Wire	Mean (A)	RMS (A)
1	161.9	216.2
2	161.9	216.2

Figure 4.17: Estimated currents for each wire based on setting parameters

4.1.3 First trials using the FlexTandem - Pulsed 1 program

In order to verify the program operation, some 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 showed that the program was working properly, some welding trials were carried out. Different combinations of parameters were tried and a data acquisition system was used to record the current and voltage signals from both wires. Figures 4.18 and 4.19 present current and voltage signals with different parameters for each wire (different waveforms) with 4 and 5 ms of delay, respectively. Figure 4.20 shows a short-circuiting event controlled by the program in wire 1. Figures 4.21 and 4.22 show a comparison between input (command from the program) and output of current for both wires.

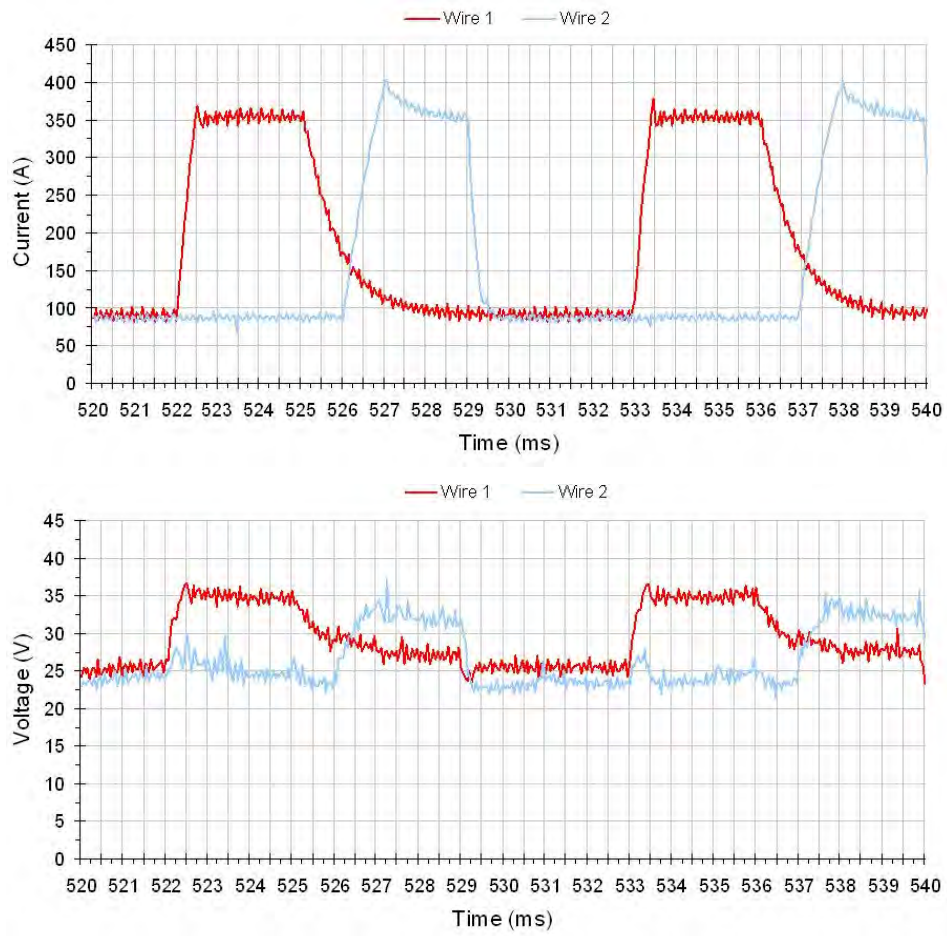


Figure 4.18: Current and voltage signals for each wire with 4 ms of delay

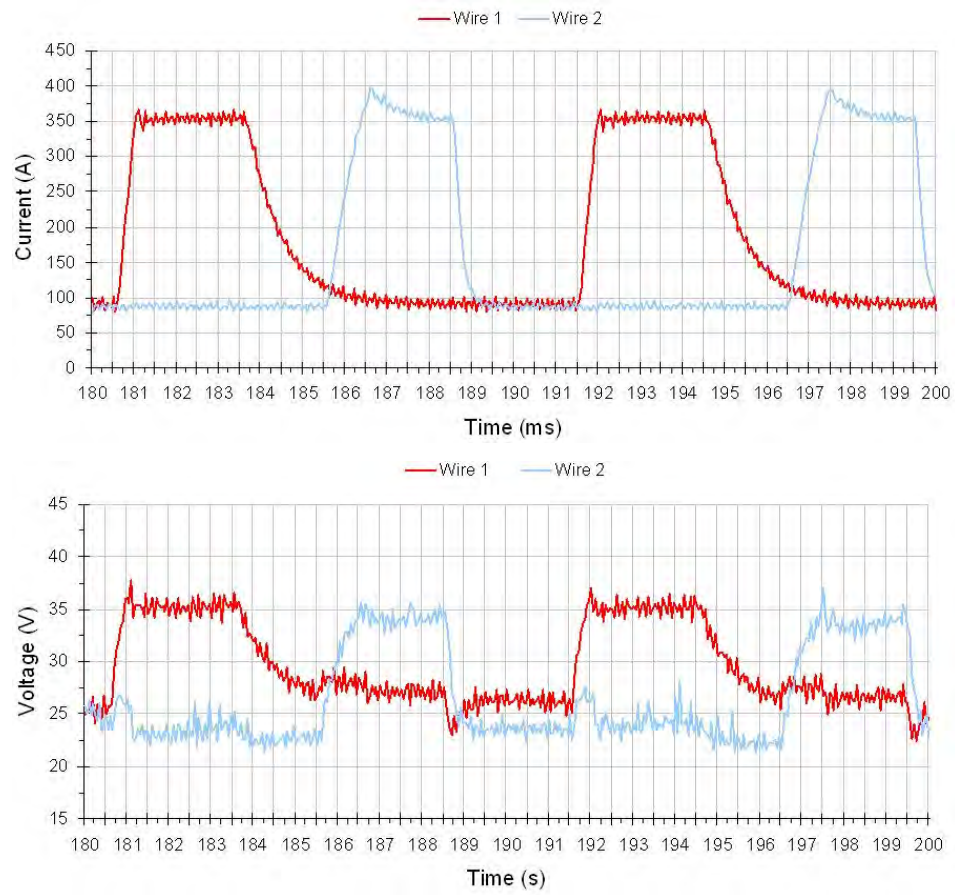


Figure 4.19: Current and voltage signals for each wire with 5 ms of delay

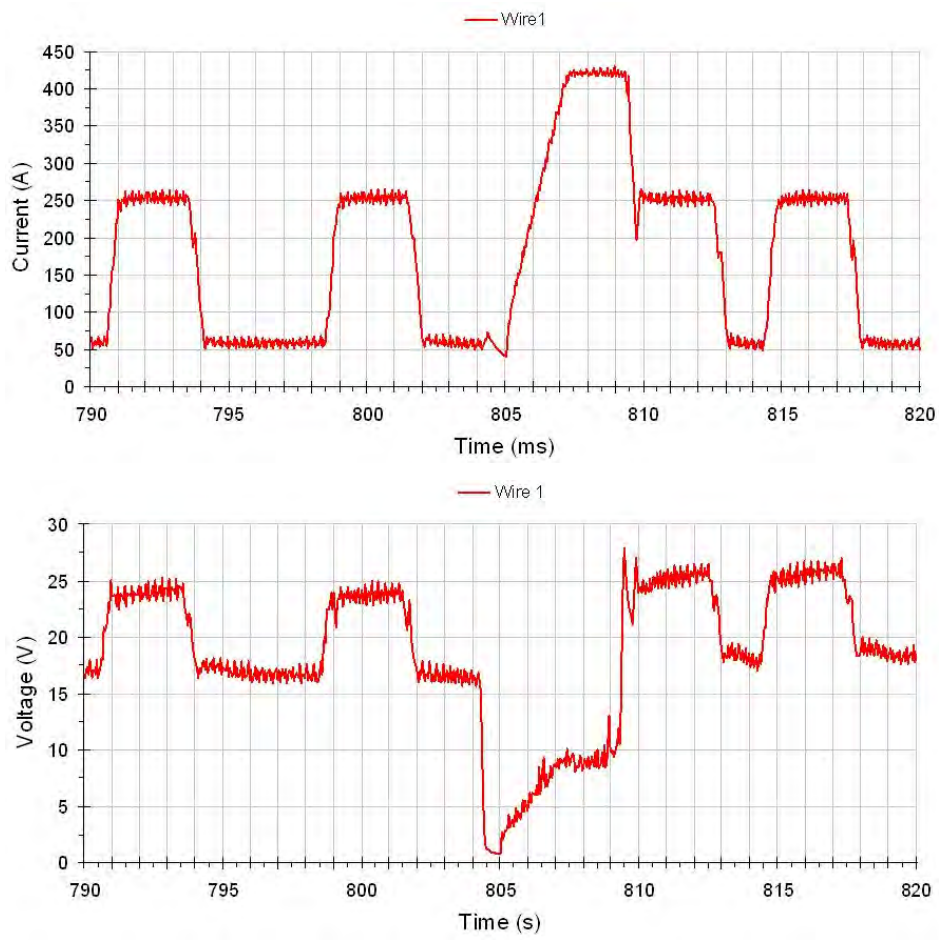


Figure 4.20: Controlled short-circuiting event in wire 1 (verifying the control efficiency)

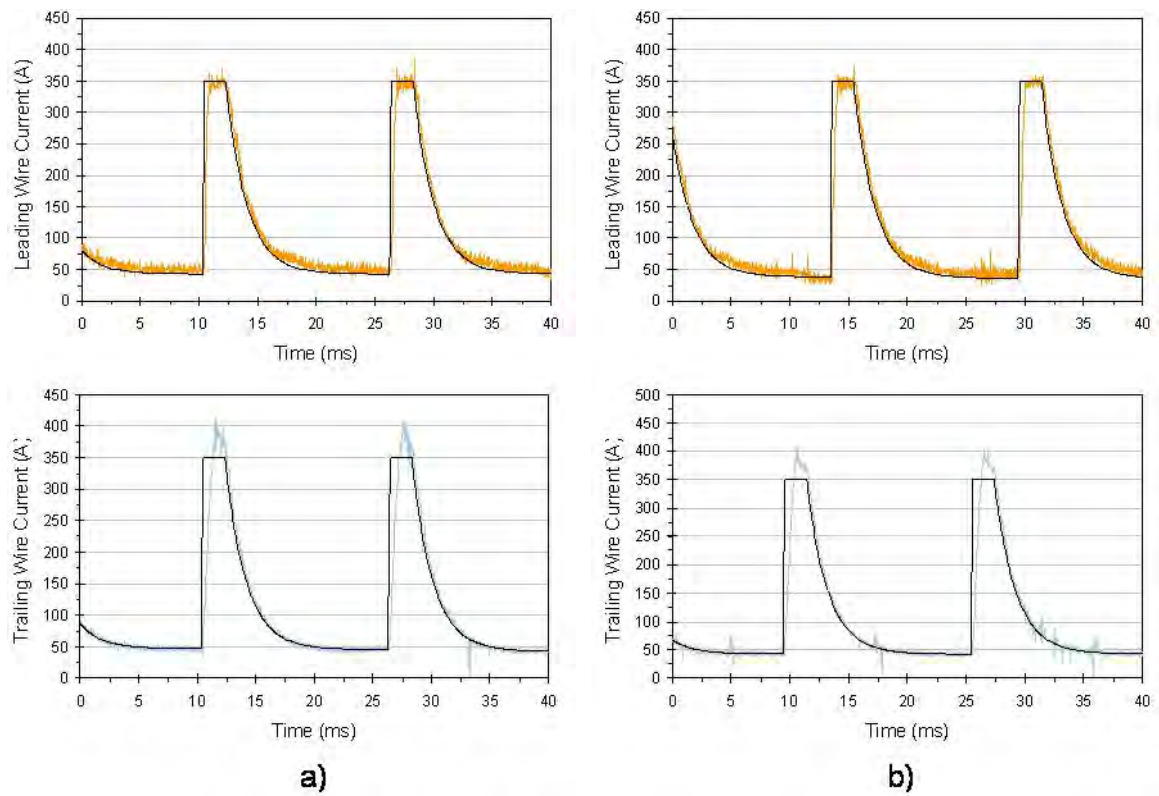


Figure 4.21: Control program current input (smooth contour) and power sources current output (rough contour) for both wires (pulses almost-in-phase in (a) and staggered in (b)) (the pattern shows that the power sources follow the control)

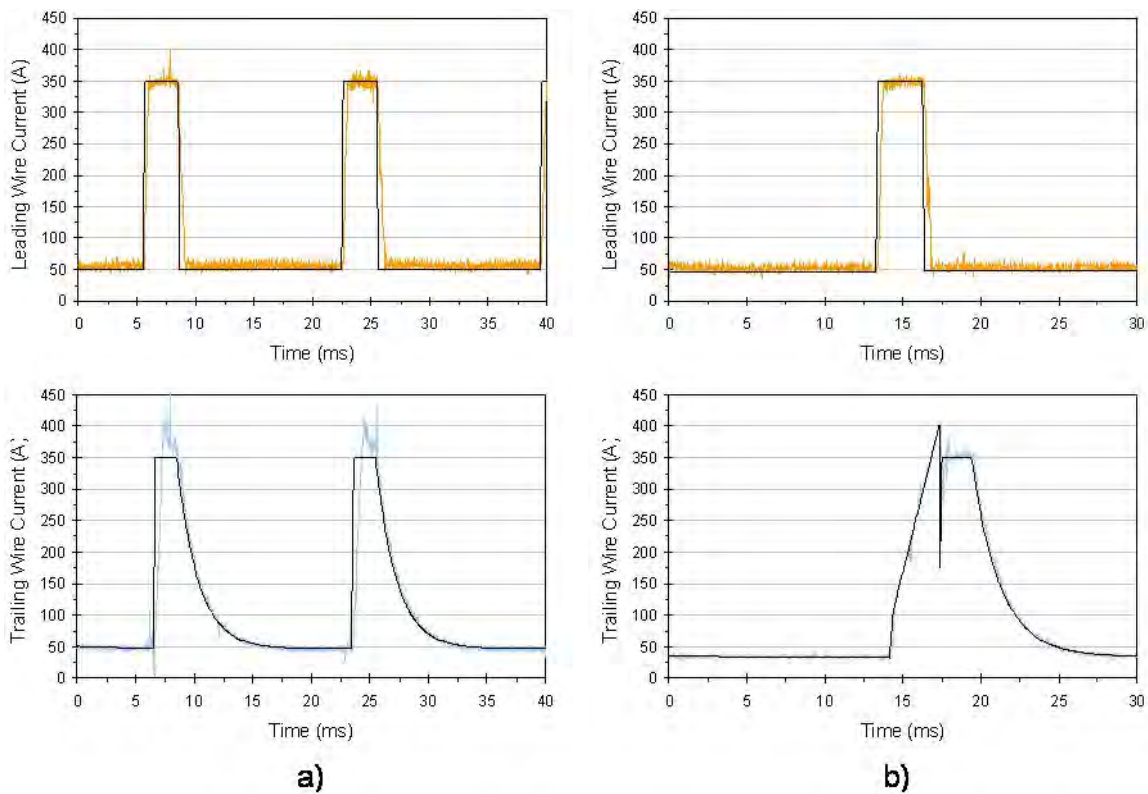


Figure 4.22: Control program current input (smooth contour) and power sources current output (rough contour) for both wires (pulses almost-in-phase but with different forms in (a) and short circuit in trailing wire in (b)) (the pattern shows that the power sources follow the control)

4.1.4 General comments

The first version of the FlexTandem program was devised for tandem pulsed GMAW and presents an amicable user interface and high flexibility for parameters setting (independence between wires). The program was totally able to control the pulsing parameters (current waveform) for both wires. By these features this program becomes an important tool to investigate tandem GMAW.

4.2 Pulsed Welding Condition with Low Mean Current

Since the main aim of this work is to assess new combinations of processes and techniques using tandem GMAW, this stage was carried out to select a basic condition for the pulsed mode. The main demands for this basic condition were a one-droplet-per-pulse transfer state, with a low mean current value and with a high level of stability/repeatability.

4.2.1 Specimen and support used

Specimens, which dimensions are shown in Figure 4.23, consisting of a mild steel thin sheet were used. Bead on plate condition was used to simplify the tests. The plates were fixed using a support in such a way that they were placed 10 mm above the welding table and using no backing plate (as a way to deal with the burn-through risk). Figure 4.24 shows how the specimens were fixed in the welding table. This specimen arrangement was kept throughout the tests described in this work.

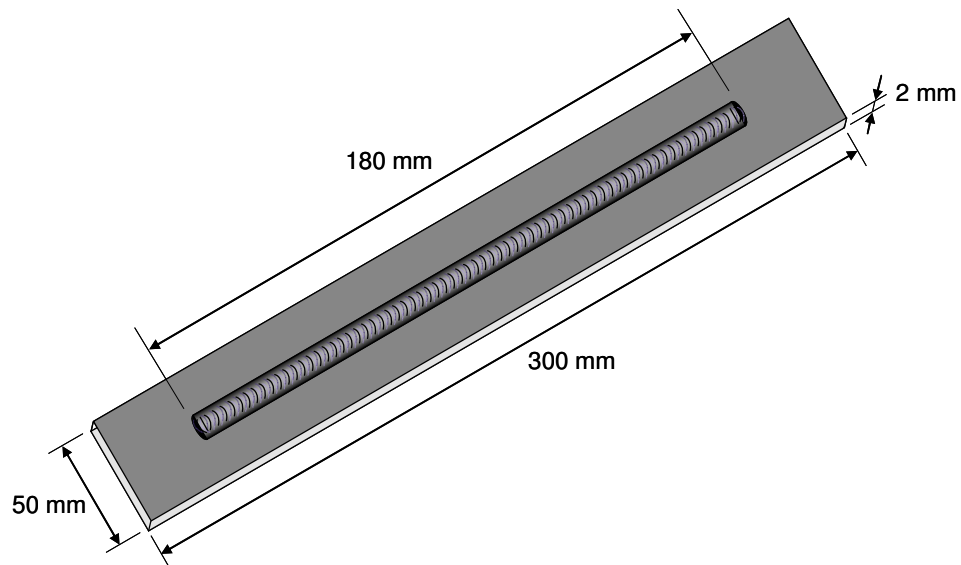


Figure 4.23: Welding specimen dimensions

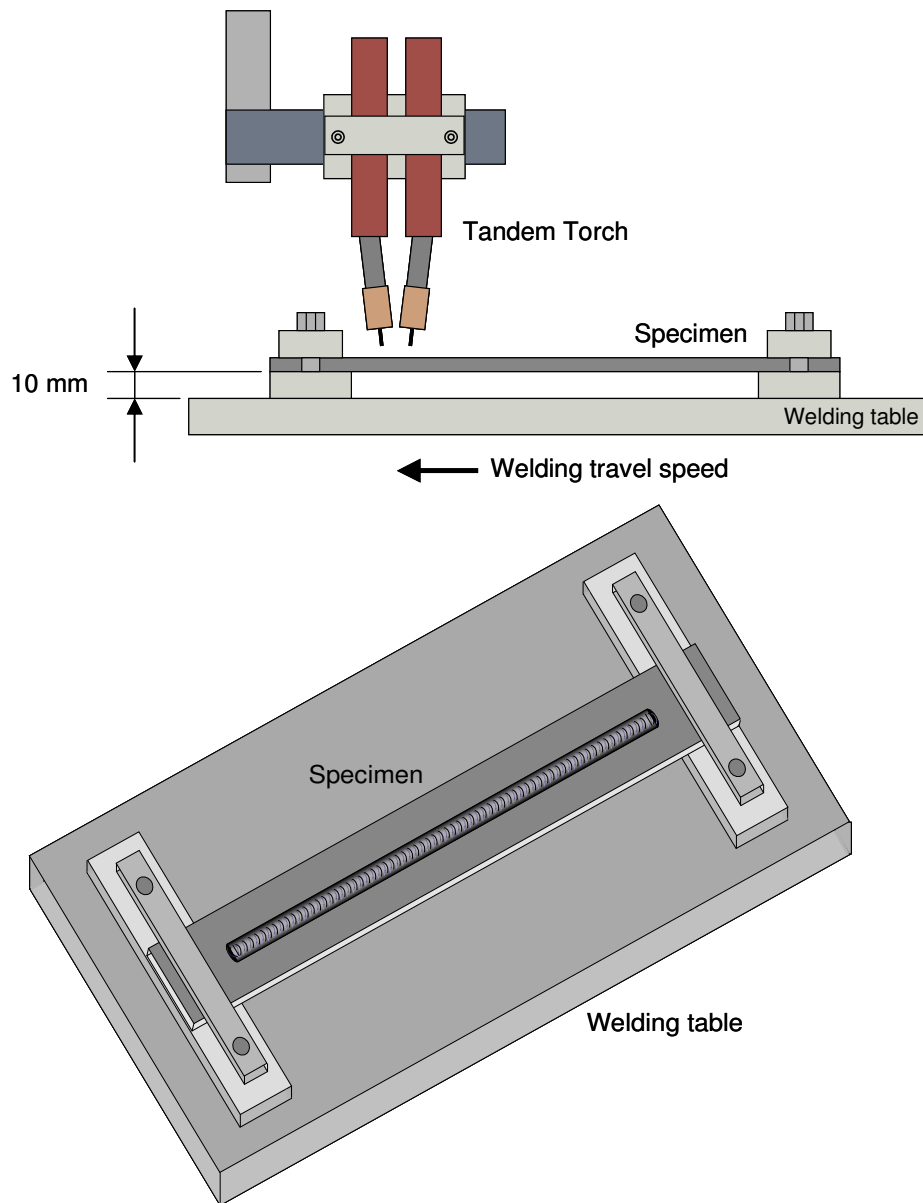


Figure 4.24: Schematic assembly for holding the specimens for welding

Table 4.4 shows the basic parameters values used for searching one-droplet-per-pulse conditions. Figure 4.25 shows how the inter-wire distance and angles between the wires were considered.

Table 4.4: Additional welding parameters

Welding Parameter	Value
CTWD* (both wires) (mm)	20
WTS (m/min)	1
Inter-Wire Distance (mm)	10
Shielding Gas [98.5% Ar + 1.5% O ₂] (l/min)	35
Inter-wire Angle (°)	35
Electrode diameter [AWS ER 70S-6] (mm)	1.2

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

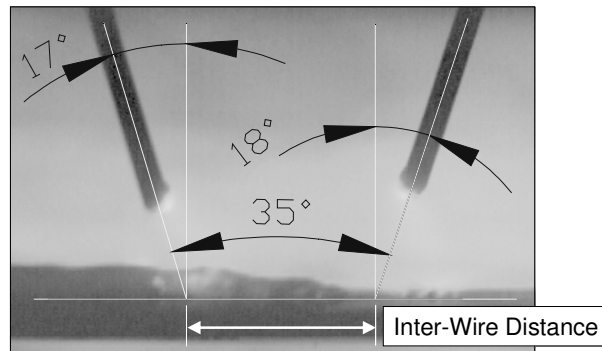


Figure 4.25: Angle measured between the electrodes and inter-wire distance parameter (trailing wire on the left side and leading on the right)

4.2.2 Conditions for one droplet per pulse

In order to find a one droplet per pulse condition, the methodology suggested by Norrish (1992) was followed and high speed video with synchronized welding data acquisition was used to verify whether the condition was achieved or not. Actually, as the methodology presented by Norrish (1992) does not consider current ramps, tail-outs, etc. and is related to single GMAW, a condition close to one droplet per pulse was found and then tuned considering the results observed from the high speed videos. The conditions were chosen also in order to keep the mean current level at around 100 A. One of the conditions was without tail-out (which means fast drop of current in the end of the pulse time) and the other one was with tail-out (which means the current reached progressively the base current level after the end of the pulse time). Tables 4.5 and 4.6 show the main setting of parameters used in these conditions. Figures 4.26 and 4.27 present, through synchronized image-data, the one droplet per pulse conditions achieved. Resulting mean values of welding current and voltage for both wires are presented in Table 4.7.

Table 4.5: Basic condition for one droplet per pulse without tail-out

Welding Parameter	Value
$I_{pulse1} = I_{pulse2}$ (A)	350
$T_{pulse1} = T_{pulse2}$ (ms)	3
$I_{base1} = I_{base2}$ (A)	40
$T_{base1} = T_{base2}$ (ms)	14
$Ramp_up1 = Ramp_up2$ (A/ms)	2000
$Ramp_down1 = Ramp_down2$ (A/ms)	2000
$Tailout1 = Tailout2$ (dimensionless)	1
$WFR1 = WFR2$ (m/min)	3.8
Delay (ms)	4

Table 4.6: Basic condition for one droplet per pulse with tail-out

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)	14
$Ramp_up1 = Ramp_up2$ (A/ms)	2000
$Ramp_down1 = Ramp_down2$ (A/ms)	2000
$Tailout1 = Tailout2$ (dimensionless)	45
$WFR1 = WFR2$ (m/min)	4
Delay (ms)	2

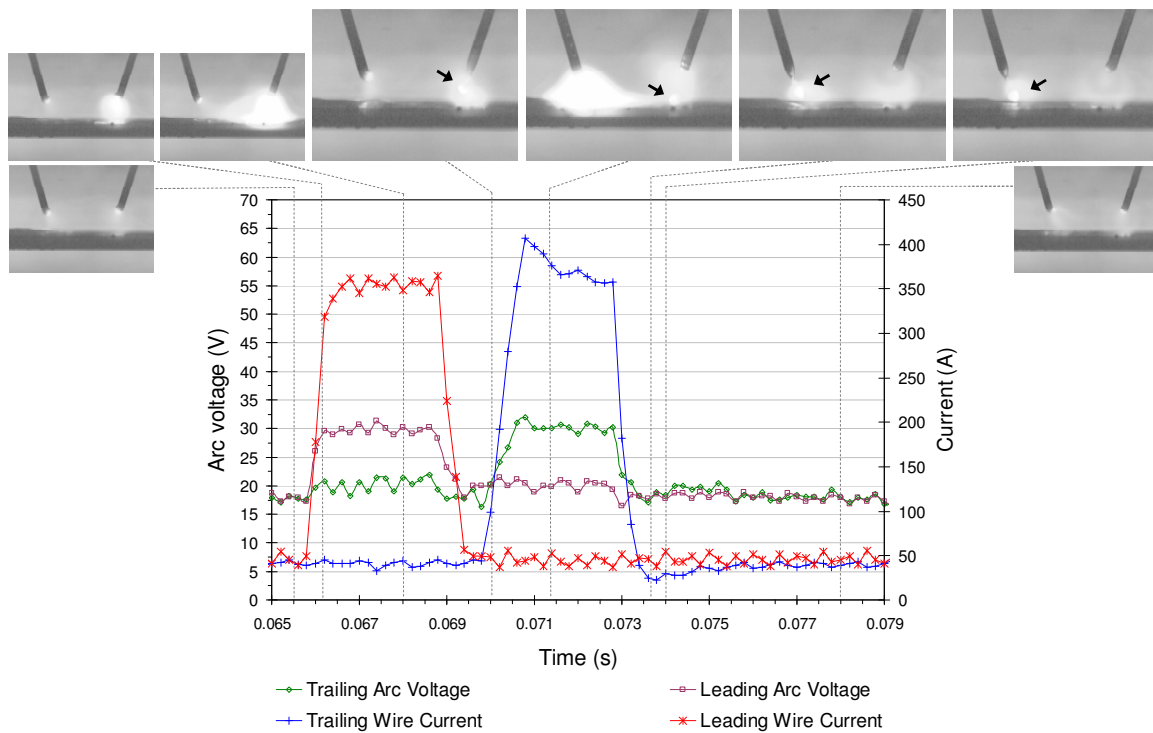


Figure 4.26: Basic condition for one droplet per pulse without tail-out (trailing wire on the left side and leading on the right) (0.125 seconds of acquisition at 5000 Hz)

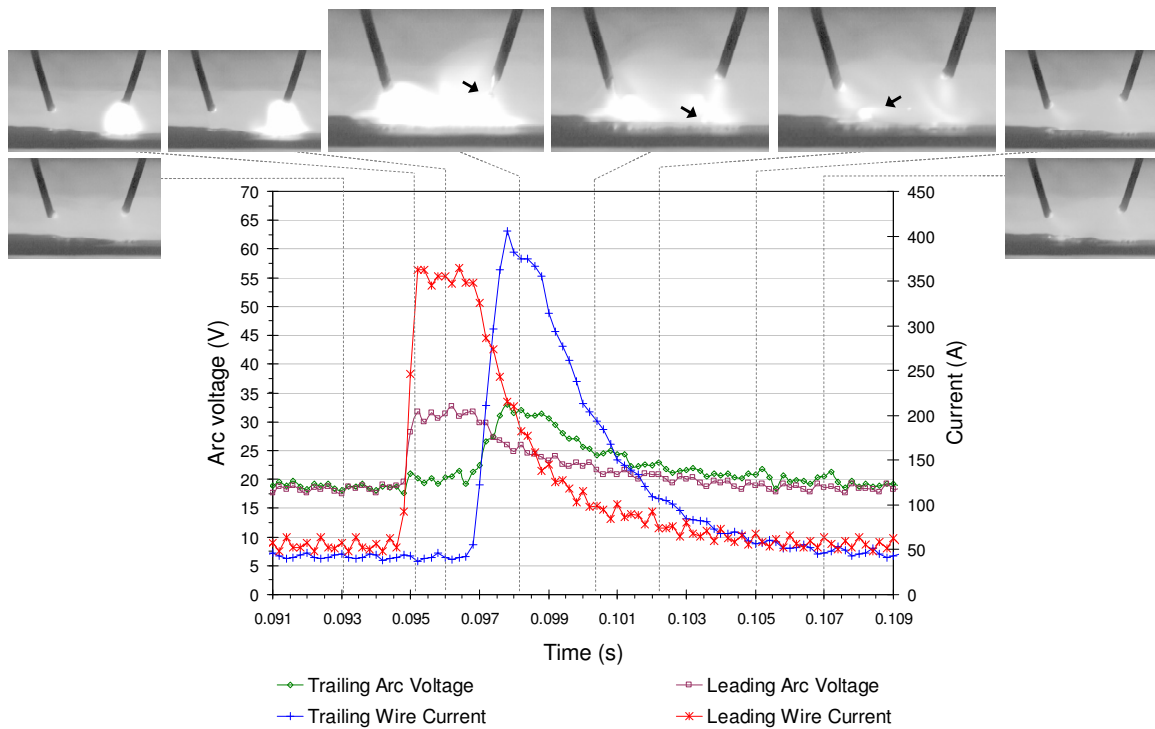


Figure 4.27: Basic condition for one droplet per pulse with tail-out (trailing wire on the left side and leading on the right) (0.125 seconds of acquisition at 5000 Hz)

Table 4.7: Mean values for welding current and voltage under basic welding conditions

Basic Welding Condition	Trailing Wire		Leading Wire	
	Mean Current (A)	Mean Voltage (V)	Mean Current (A)	Mean Voltage (V)
Without Tail-Out	88.8	25.10	101.9	20.67
With Tail-Out	105.7	21.69	110.4	21.22

Even though these two basic conditions were adequate for one droplet per pulse condition, arc interruptions were observed mainly for the condition without tail-out, which indicates that the pulse should be set with tail-out. These arc interruptions were similar to those presented by Ueyama et al. (2005) and an arc interruption event is shown in Figure 4.28. As it would be expected, the interruption is marked by arc voltage rise to the open circuit value as the current drops to zero (this fact explains the major difference in mean current and voltage values between the wires for the basic welding condition without tail-out on Table 4.7). Before the extinction, the arc links with the other arc in a very peculiar phenomenon. This arc migration from the plate to the other electrode was also observed by Ueyama et al. (2005). As these interruptions may lead to variation in the amount of energy and molten wire delivered to the plate, they must be avoided or minimized. Two aspects can be considered regarding the arc interruptions, the frequency and the duration of them. The higher the interruptions frequency and/or duration, the bigger might be the deterioration in the bead formation. Figure 4.29 illustrates an example of bead appearance with very long arc interruptions. The lack of molten metal on the face of the bead is obvious and the effect on penetration can be seen by the variation of the heat affected zone on the root (back of the plate). Figure 4.30 shows an abnormal voltage event. In this case the arc in the trailing wire was able to “recover” from the disturbance before it was extinguished (the event is marked by a voltage increase beyond the expected level). Figure 4.31 shows the theoretical arc displacements based on the model presented in Figure 2.24 (a detail of the time interval of Figure 4.30 is shown; the actual welding currents were used and the mean arc lengths were measured from the weld images).

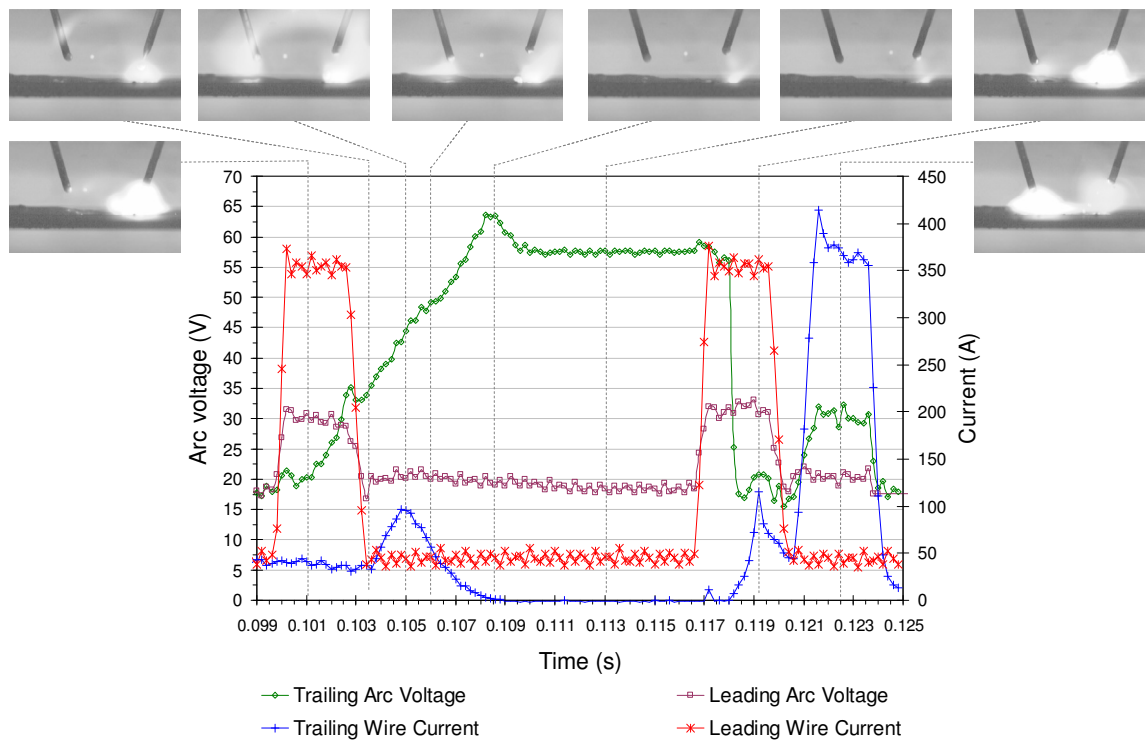


Figure 4.28: Example of arc interruption occurring in the trailing wire (trailing wire on the left side and leading one on the right)

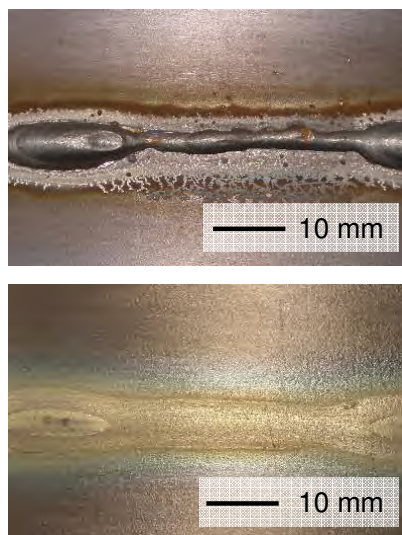


Figure 4.29: Example of weld bead appearance (face and root) with very long arc interruptions in the trailing arc

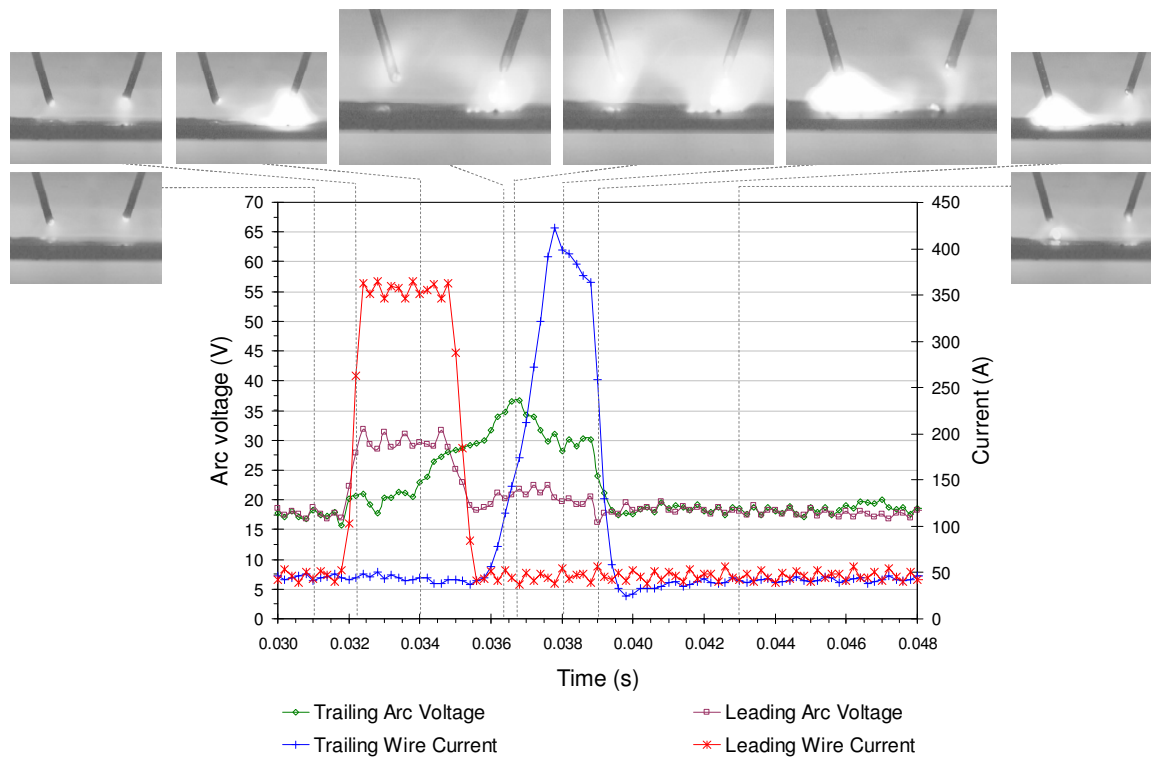


Figure 4.30: Example of abnormal voltage occurring in the trailing wire (trailing wire on the left side and leading on the right)

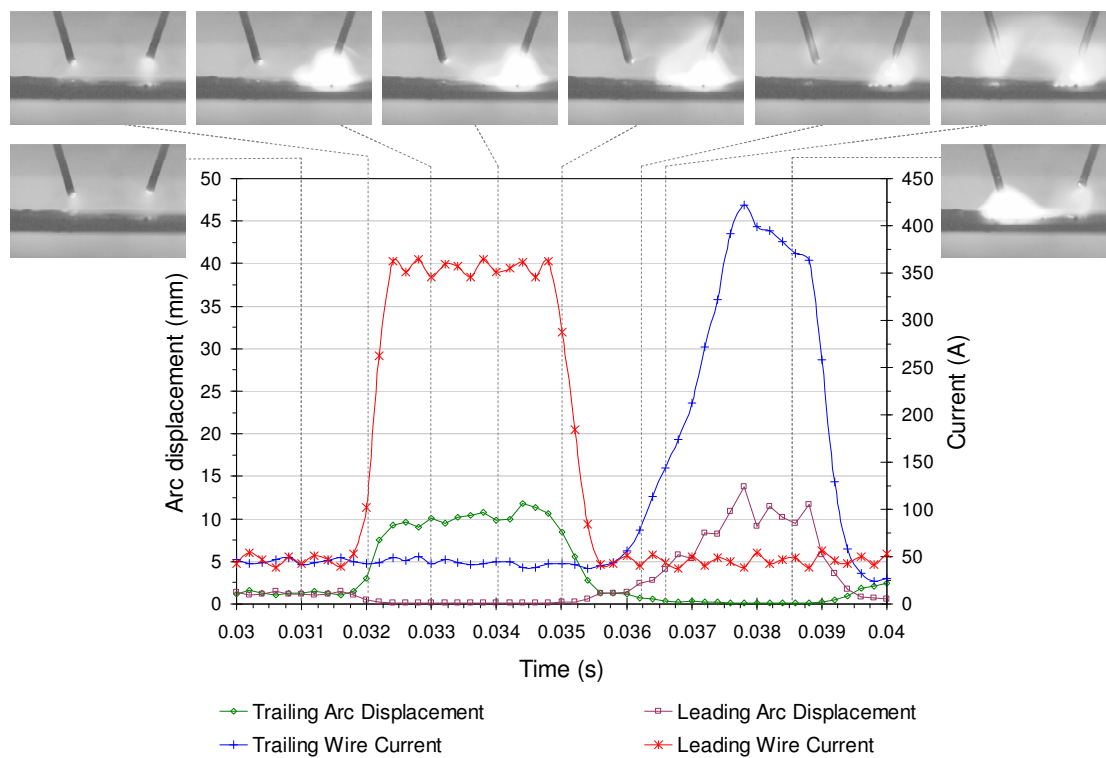


Figure 4.31: Theoretical arc displacements based on the model presented in Figure 2.24 (detail of the time interval of Figure 4.30)

By watching the videos when the arcs are in the base current level, it was possible to see that the trailing arc wanders over the weld pool more than the leading arc does. Although the wandering of the trailing arc is much clearer in the video, an idea of such instability is given by Figure 4.32 (the arc seems to be without stable cathode spots). Along with the attraction of the trailing arc by the leading arc, this fact is likely to contribute with the trailing arc interruption as shown previously by Figure 4.28. So, it seems that arc interruptions are related basically to two factors:

- Interaction between the arcs; and
- Instability of cathode spots.

The influence of the cathode spots also seems to justify the reason why the leading wire usually does not have many interruptions (as the leading arc has more stable cathode spots it offers more resistance to the interruption). Figure 4.33 illustrates schematically how the trailing arc moves from its normal “vertical” position (trailing wire to weld pool) to the abnormal “horizontal” position (trailing wire to leading wire). As the reason why the arc is extinguished remains still obscure, further investigation concerning this topic is carried out in Chapter V.

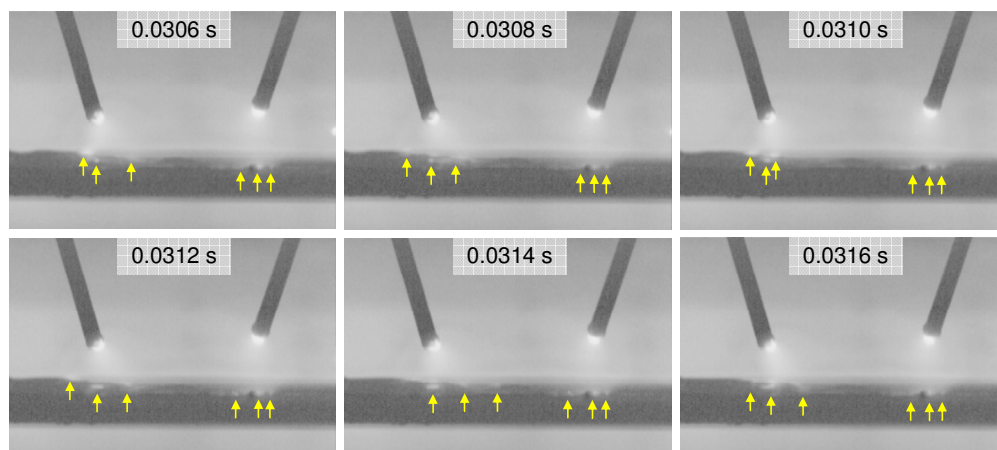


Figure 4.32: Sequence of welding time showing the trailing arc wandering over the pool
(movement of cathode spots indicated by arrows)
(trailing wire on the left side and leading on the right)

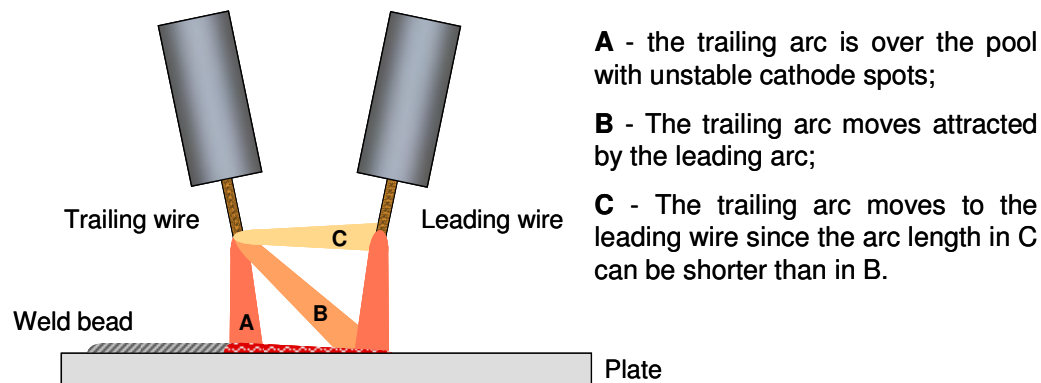


Figure 4.33: Illustration on how the trailing arc changes its position before the interruption

In the search for a more stable and robust basic condition for tandem pulsed GMAW, a general evaluation of the delay and plate surface condition effect and of the wire inter-distance effect was carried out. The basic condition with tail-out (Table 4.6) was used to provide the constant parameters throughout the tests since it has a higher base current value than that one without tail-out. Ueyama et al. (2006) verified that the number of interruptions decreased with the rise in the base current value.

4.2.3 Delay and plate surface condition effect

A number of tests were carried out with mill scaled (as received) and clean (without mill scaled on the surface) plates. Table 4.8 presents the delays tried with the respective plate surface states (the inter-wire distance was kept in 10 mm throughout the tests and all further parameters also followed the basic condition with tail-out). As a method to remove the mill scale entirely, the plates were etched with hydrochloric acid followed by a mechanical brushing. Three welding beads were produced for each delay value. The first bead was used to provide images (high speed video at 5000 frames per second) synchronized with welding data (0.125 seconds of data acquisition at a 5000 Hz rate), while two extra beads were used to record the welding data for arc interruptions and abnormal voltages assessment and further process statistics (4 seconds of data acquisition at a 5000 Hz rate).

Table 4.8: Delay values tested

Delay (ms)	Plate Surface Condition	
	Clean	Scaled
0.1	X	X
0.5	X	
1.0	X	
2.0	X	X
8.0	X	X
14.0	X	

Based on previous tests, an interruption was considered to occur each time the arc voltage rose above 60 V (Figure 4.28), while an abnormal voltage was regarded as each rise of voltage beyond 35 V (Figure 4.30). A Microsoft Excel® datasheet was devised to count these events once the welding data file is loaded into it (the number of abnormal voltages includes any arc interruption). Only events happening in the trailing arc were evaluated since the leading arc has been shown to be far less prone to abnormal voltages and/or arc interruptions (Ueyama et al. (2005) and from previous exploratory tests). None of the tests with clean plates produced interruptions and the number of abnormal voltages was far smaller than when using scaled plates (Figure 4.34), indicating that the presence of mill scale deteriorates the welding stability. In the case of scaled plates, the use of small delays is in favor of stability since it reduces the number of abnormal voltages.

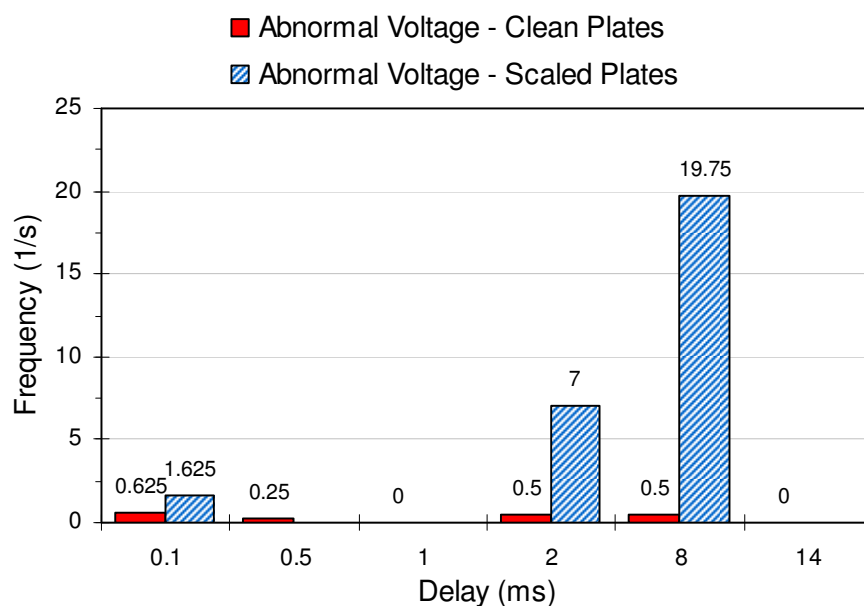


Figure 4.34: Abnormal voltage frequency for clean and scaled plates under different delays (trailing wire)

Unlike the clean plates, the scaled plates produced a number of arc interruptions. Figure 4.35 shows a situation of welding transition (bead and electrical signals) from a scaled to a clean part of the plate. It is clear the incidence of arc interruptions (primary spikes) and abnormal voltages (secondary spikes) while in the first half of the plate (scaled) and the absence of such events in the second half (clean). In this case the arc interruptions did not compromise the quality of the bead since they had a very short duration.

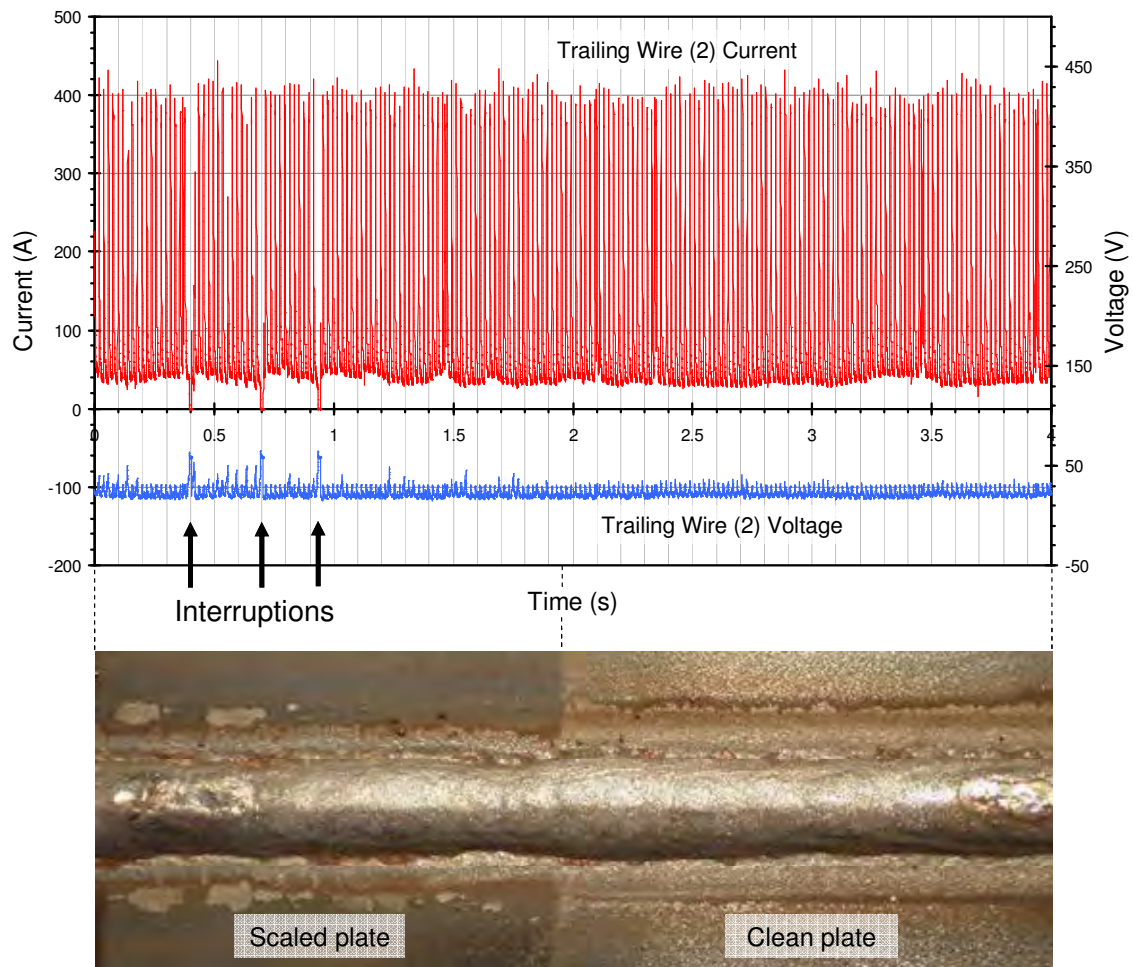


Figure 4.35: Effect of plate surface condition on arc interruption incidence (basic condition with tail-out and delay of 8 ms) (welding from left to right)

As shown by Table 4.9 and Figure 4.36, the number of arc interruptions has a similar tendency to that presented by the abnormal voltages (the frequency of the events increases as the delay value increases). However, the delay of 0.1 ms (almost in phase current pulses) was able to produce absence of arc interruptions, despite the small number of abnormal voltages occurred. This result presents accordance to what was presented by Ueyama et al. (2006), whose work shows that a delay small as 0.5 ms avoided the trailing arc interruptions.

Table 4.9: Arc interruptions and abnormal voltages for scaled plates under different delays
(trailing wire)

Delay (ms)	Number of Arc Interruptions				Number of Abnormal Voltages			
	Value 1	Value 2	Mean Value	Frequency* (1/s)	Value 1	Value 2	Mean Value	Frequency* (1/s)
0.1	0	0	0	0	8	5	6.5	1.62
2	1	3	2	0.5	18	38	28	7
8	43	23	33	8.25	77	81	79	19.75

* Frequency of arc interruption and abnormal voltage value calculated for a 4 seconds time interval

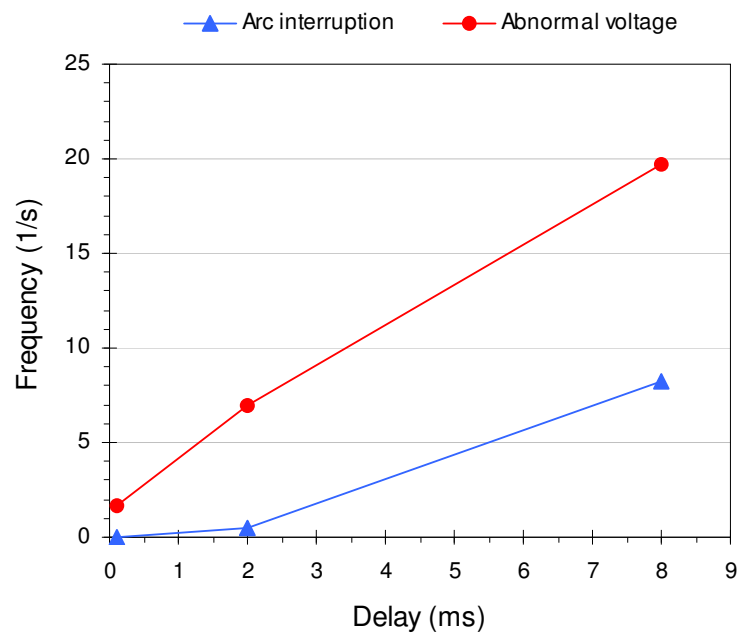


Figure 4.36: Influence of delay on arc interruption and abnormal voltage frequency
(trailing wire)

Figures 4.37 and 4.38 show the general appearance of those beads produced under different delay values and plate surface conditions. Excluding the beads produced on scaled plates and with an 8 ms delay (high arc interruption frequency), all beads had similar and good appearance. Figure 4.39 shows a bead (face and root) produced on scaled plate and under an 8 ms delay in detail. It is worth noting how the bead volume and heat affected zone vary along the bead, indicating that arc interruptions (wire deposition and heat source interruptions) may lead to lack of deposition and fusion/penetration defects.

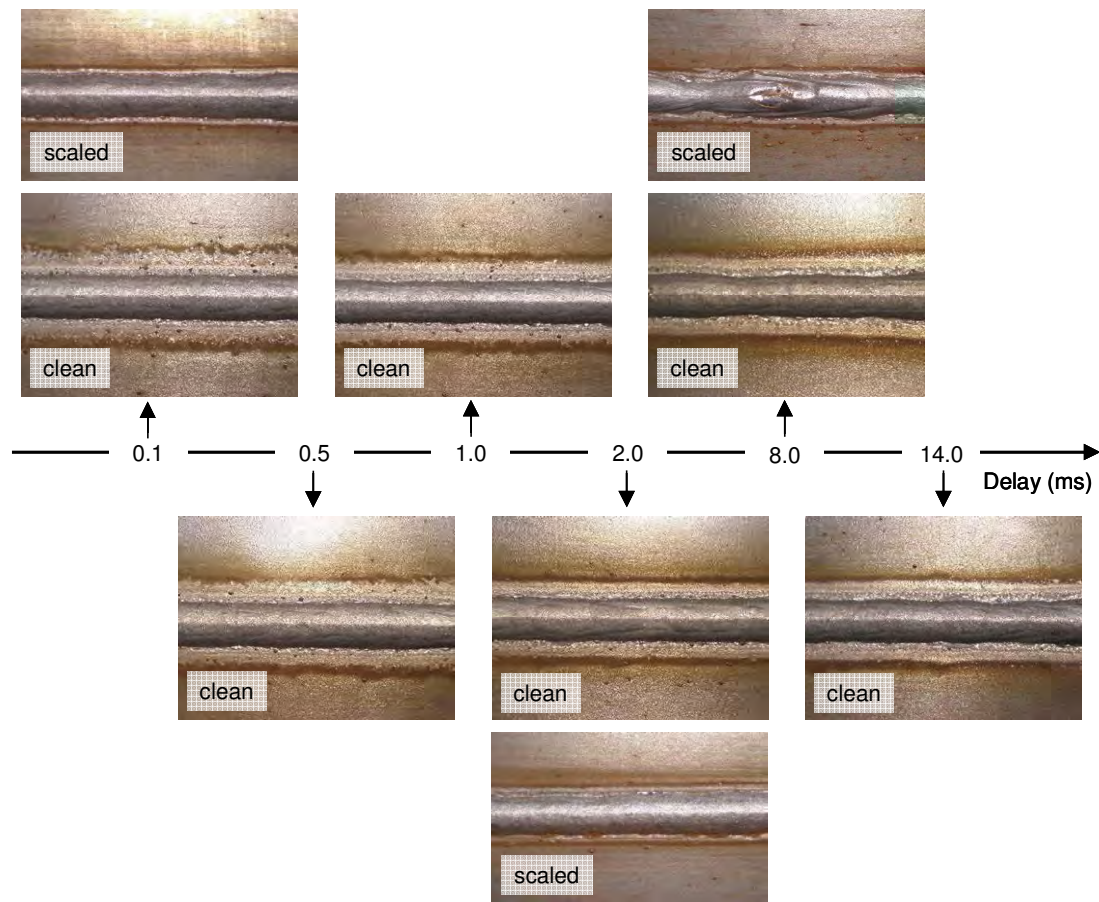


Figure 4.37: Typical bead appearance under different delays and plate surface conditions



Figure 4.38: Typical appearance of root for weld beads of Figure 4.37

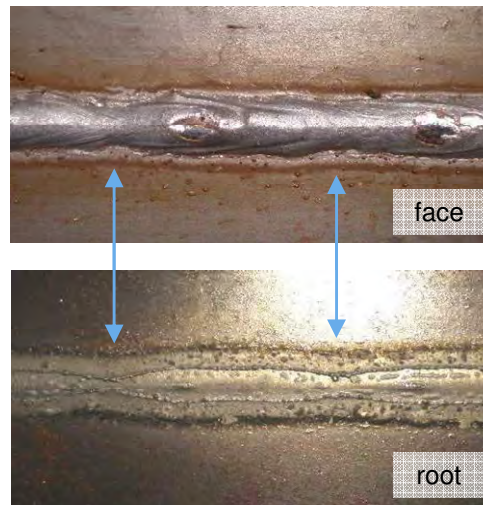


Figure 4.39: Typical appearance of weld beads on scaled plates and with an 8 ms delay (position of long arc interruptions indicated by arrows)

Despite the scale layer thickness was not measured, it seems to be enough to limit a good cathodic emission. Probably, up to a certain amount, the presence of scale (oxides) should help on cathodic emission, but for some reason the condition for the trailing arc when welding on scaled plates favours the occurrence of interruptions. The superficial roughness of the plates after removing the mill scale could be also a factor influencing the absence of interruption. At this point it is hard to prove it, but, depending on the scale presence or not, the arc composition could be also different for each arc, which could influence on the interruptions as well. The reason why the scale causes more interruptions and why the interruptions concentrate on the trailing arc remains unclear and requires more investigation.

Anyway the use of a very small delay (0.1 ms) between the pulses of current of each wire solves the interruption problem, regardless of welding on scaled plates or not.

4.2.4 Inter-wire distance effect

With the purpose of verifying the effect of the inter-wire distance, a number of tests were carried out using scaled plates and with a delay value of 0.1 ms throughout the tests (all further parameters followed the basic condition with tail-out). This delay value was used since it showed to be more robust (no interruptions with scaled or clean plates). Table 4.10 presents the inter-wire distances tested. Three welding beads were produced for each inter-wire distance. The first bead was used to supply images (high speed video at 5000 frames per second) synchronized with welding data (0.125 seconds of data acquisition at a 5000 Hz rate), while the extras beads were used to record the welding data for arc interruptions and

abnormal voltages assessment and further process statistics (4 seconds of data acquisition at a 5000 Hz rate).

Table 4.10: Inter-wire distances tested

Inter-Wire Distance (mm)	Plate Surface Condition	
	Clean	Scaled
10		X
15		X
20		X
30		X

The criteria utilized to determine if an abnormal voltage and arc interruption occurred were the same used for the delay effect evaluation (abnormal voltage for voltages beyond 35 V and arc interruption for voltages above 60 V). As considered before for the delay effect case, only events happening in the trailing arc were evaluated. As shown by Table 4.11 and Figure 4.40, the frequency of arc interruptions were very low for distances shorter than 15 mm and a peak in the frequency of interruptions occurred for 20 mm (the abnormal voltage curve had the same tendency). Similar tendency was observed in studies conducted by Ueyama et al. (2005), where a peak in the number of arc interruptions and abnormal voltages occurred for a 10 mm inter-wire distance when using 80% Ar and 20% CO₂ as shielding gas.

Table 4.11: Arc interruptions and abnormal voltages for different IWDs (trailing wire)

Inter-Wire Distance (mm)	Number of Arc Interruptions				Number of Abnormal Voltages			
	Value 1	Value 2	Mean Value	Frequency* (1/s)	Value 1	Value 2	Mean Value	Frequency* (1/s)
10	0	0	0	0	8	5	6.5	1.625
15	0	1	0.5	0.125	6	18	12	3
20	9	9	9	2.25	22	20	21	5.52
30	0	0	0	0	8	4	6	1.5

* Frequency of arc interruption and abnormal voltage value calculated for a 4 seconds time interval

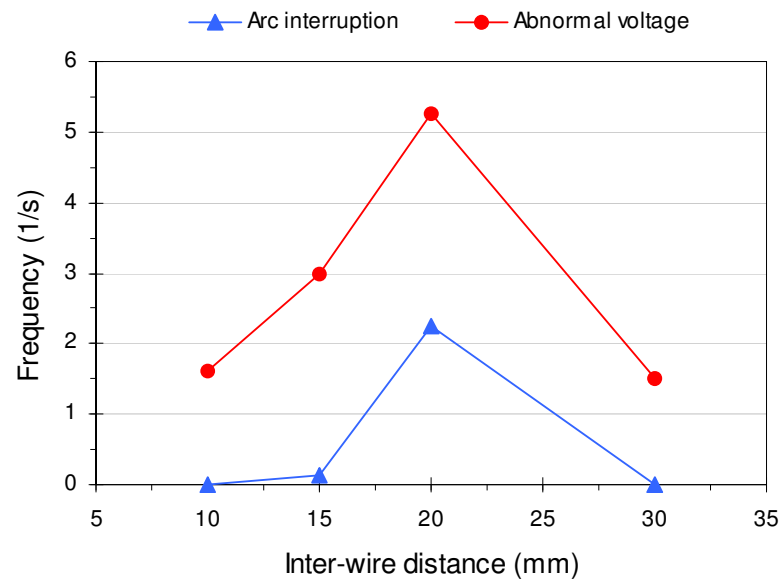


Figure 4.40: Influence of inter-wire distance on arc interruption and abnormal voltage frequency

Despite the absence of interruptions also with an inter-wire distance of 30 mm, this condition is not recommended since the arcs were acting on two distinct weld pools. This condition certainly diminishes the tandem GMAW positive effect on penetration, for example.

Figure 4.41 and 4.42 show the general appearance of the weld beads produced under different inter-wire distances. All beads had similar and good appearance, with shorter distances slightly favouring a better appearance on the bead face. This fact also indicates that 10 mm, and not 30, should be used as the inter-wire distance.

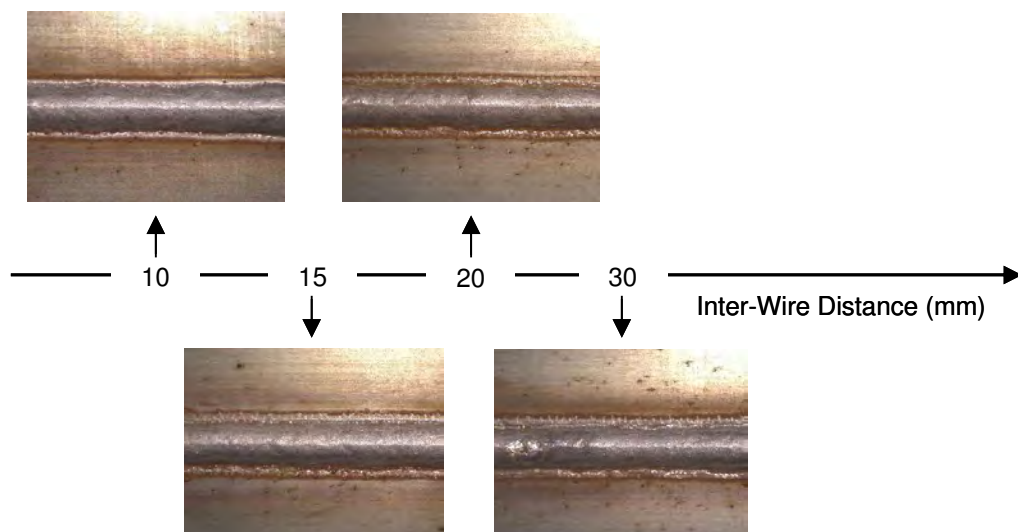


Figure 4.41: Typical weld bead appearance under different inter-wire distances



Figure 4.42: Typical root appearance for weld beads of Figure 4.41

Figure 4.43 shows the overall appearance of weld beads produced with the best welding condition found (0.1 ms of delay, 10 mm of inter-wire distance and further parameters according to the basic welding condition with tail-out previously defined). The weld cross section produced with this condition is shown by Figure 4.44, while Table 4.12 presents the mean welding currents and voltages reached.

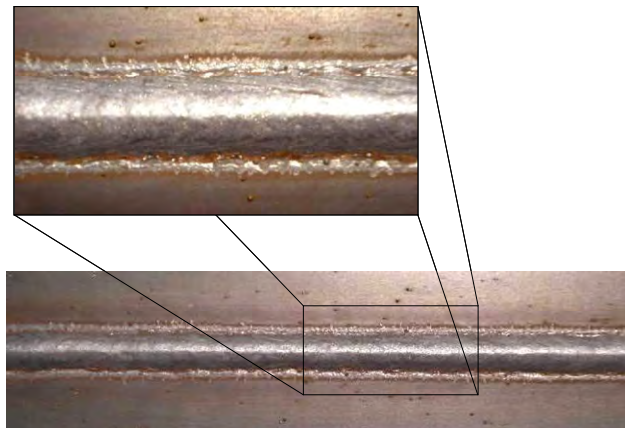


Figure 4.43: Overall appearance of beads produced with the best welding condition

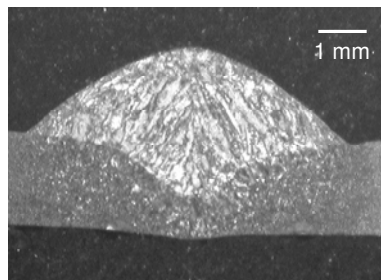


Figure 4.44: Example of cross section of beads produced with the best welding condition

Table 4.12: Mean values for current and voltage under the best welding condition

Weld Bead	Trailing Wire		Leading Wire	
	Mean Current	Mean Voltage	Mean Current	Mean Voltage
First	103.3	21.21	112.2	21.62
Second	103.2	21.92	113.4	21.73
Third	103.8	22.05	113.3	21.81

4.2.5 General comments

In the search for a basic pulsed welding condition able to produce one droplet per pulse of current, disturbances in the trailing arc were observed (the leading wire did not present a similar problem). These events, characterized by arc interruptions, can lead to lack of deposition and fusion/penetration defects, since they cause wire deposition and heat source interruptions. They seem to be related to arc interaction (attraction), since the interruption in one arc takes place when the other arc is rising to the current pulse level. Despite the trailing arc showed more instability of cathode spots, it is hard to affirm anything regarding the relationship between the interruptions and the instability of cathode spots. The mill scale (oxides) on the surface of the plates even favoured the incidence of arc interruptions and if the inter-wire distance is increased, up to a certain point, the number of interruptions increases (clean plates and small distances helped in avoiding interruptions in the trailing arc).

The results of this general investigation on the effect of the delay between the pulses of current, the plate surface condition and the inter-wire distance eventually led to a basic condition for tandem pulsed GMAW. It was verified that, at least for low levels of mean current, the pulses of current from the leading and trailing wire need to be almost-in-phase (very small delay time) in order to minimize abnormal voltages and avoid arc interruptions in the trailing wire, regardless of the plate surface (scaled or not). This fact was verified to be in accordance with the current literature.

4.3 Tandem GMAW with Controlled Short-Circuit Waveform

As a means of allowing the use of a controlled short-circuit GMAW as a tandem process, a program was built (TandemOptarc - Version 1). The new program was built also in order to offer an amicable user interface, allowing all the parameters to be seen in the same screen and “one click” parameters setting.

4.3.1 Introduction

A controlled short-circuit GMAW process was developed at University of Wollongong by the welding research group. Further details about the process methodology can be found in Dean (2003) and in the US patent 6,512,200. The original concept was devised to deliver a method of electrical control for the short-circuit transfer mode capable to provide the following benefits:

- Reduced spattering levels compared to conventional voltage control;
- Improved stability and recovery from disturbances during the welding procedure;
- More consistent heat input control;
- Greater tolerance to poor fit-up and variable-geometry joints;
- A significantly lower cost implementation than alternative systems such as the Lincoln STT[®];
- Ability to implement control system into a generic inverter-based multi-process welding power source.

The process developed is an adaptive current-controlled process that instantaneously adjusts the power source output current to maintain stable welding conditions. It can be readily implemented in software embedded into a microcontroller-based power source. To date, development has been performed using equipment that can cycle through the control code at 25 kHz (40 microseconds). This is in excess of process requirements since a program cycle time of 100 microseconds (10 kHz) is considered to be adequate. As the short-circuit transfer welding cycle can be considered to occur in a finite number of sequential steps or states, the output current of the power source is controlled in different ways, depending on the state of the welding process. Regarding this concept, the controller is programmed as a finite-state machine and the transition between states is determined mainly by changes in the welding process instantaneous voltage, and sometimes by pre-determined time limits.

4.3.2 Description

As both wires are controlled independently (there is no dependence between the wires or any kind of synchronisation) but with the same control structure, the following description makes reference to wire 1 (leading) as a manner of illustrate how the process works. The process works exactly the same way for wire 2 (trailing) (the codes for both wires are executed in parallel). Figure 4.49 illustrates the welding current reference waveform and a resultant voltage waveform for the case, where all possible welding states are encountered in one welding cycle (abnormal situation). Figure 4.50 illustrates the welding current reference waveform and a typical resultant voltage waveform for a normal operating condition, where a reduced number of welding states are encountered in the welding cycle. It is worth saying that the current is always determined by the controller and power source, whilst the voltage is a result of physical events in the process (arc length, shielding gas, resistance of electrode, stick-out, etc.). Tables 4.13, 4.14 and 4.15 list all parameters that can be set in the TandemOptarc program and present a summarized description of their purpose. The state diagram for the TandemOptarc control process is shown in Figure 4. 51

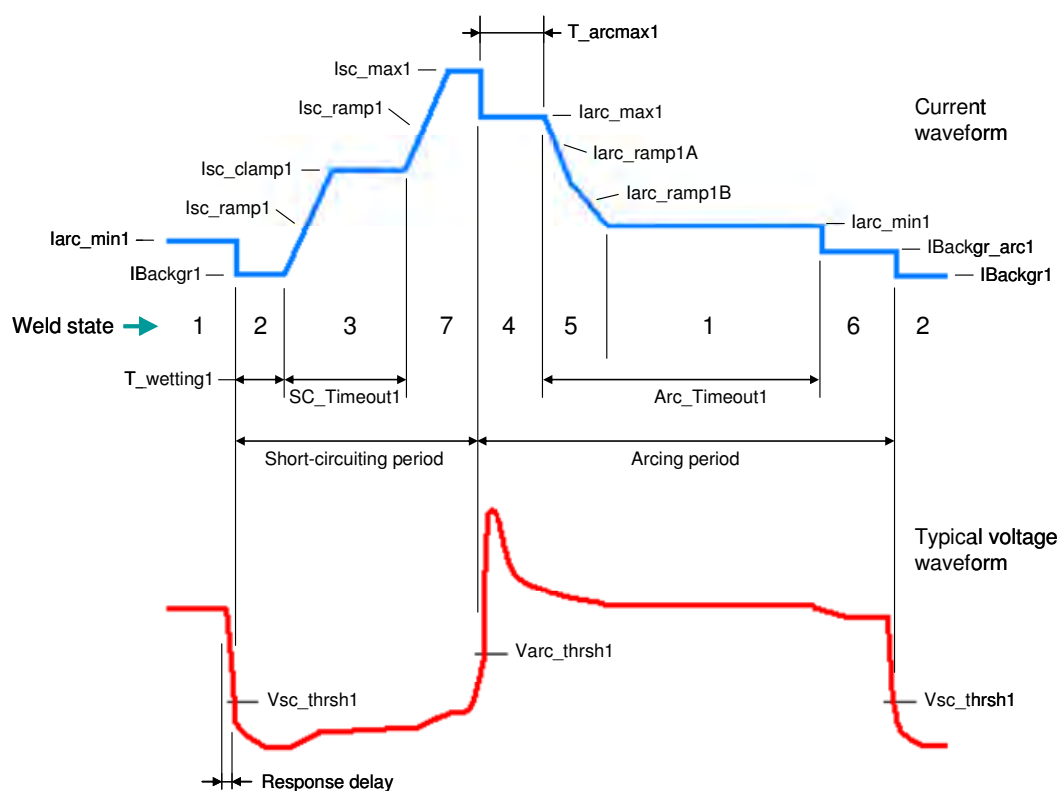


Figure 4.49: Scheme of current and voltage waveforms generated by the TandemOptarc program showing all operating states (wire 1)

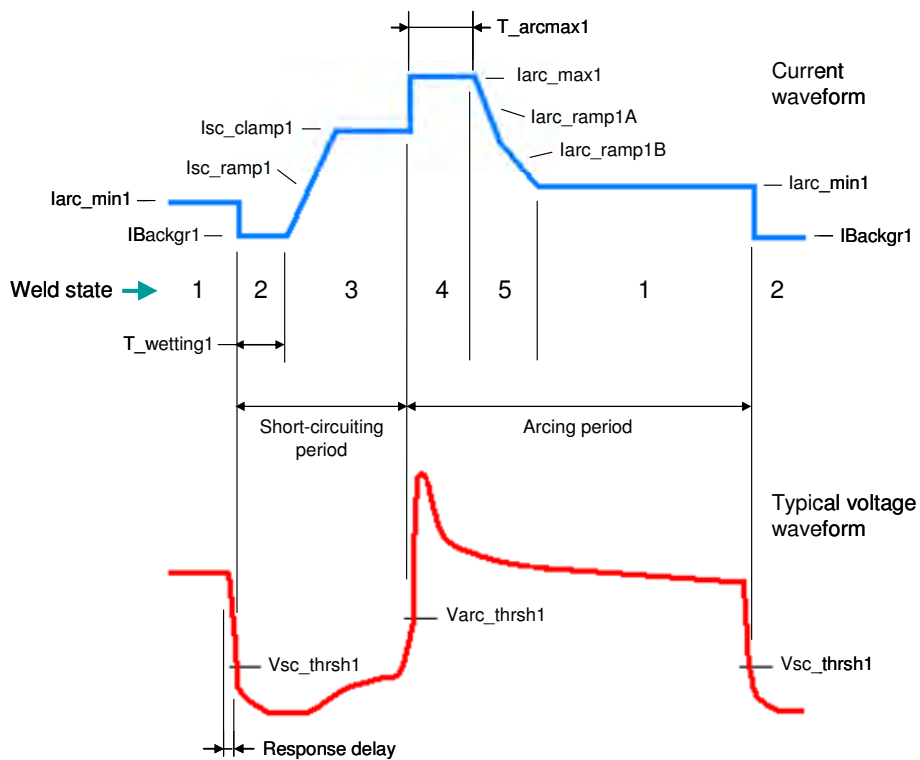


Figure 4.50: Scheme of current and voltage waveforms generated by the TandemOptarc1 program for normal process operation (wire 1)

Table 4.13: List of parameters for wire 1 in the TandemOptarc 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 4.14: List of parameters for wire 2 in the TandemOptarc program

Parameter [units]	Summarized description and/or purpose
Welding parameters	
Isc_ramp2 [A/ms]	current rising rate during short circuiting in wire 2
Isc_Clamp2 [A]	short-circuit clamp current level for wire 2
SC_Timeout2 [ms]	maximum time allowed for wire 2 in short-circuiting state
Isc_max2 [A]	maximum current allowed for short circuiting in wire 2
Iarc_max2 [A]	maximum current (pulse) applied when wire 2 returns to arc state
T_arcmax2 [ms]	time applying Iarc_max2
Iarc_ramp2A [A/ms]	initial current decreasing rate from Iarc_max2 current level
Iarc_ramp2B [A/ms]	final current decreasing rate from Iarc_max2 current level
Iarc_min2 [A]	low current value applied to wire 2 during the arc state
Arc_Timeout2 [ms]	maximum time allowed for wire 2 in arc state
IBackgr_arc2 [A]	minimum current applied to wire 2 in case of excessive arc state period
IBackgr2 [A]	current applied to wire 2 in detection of a short-circuiting event
T_wetting2 [ms]	time applying IBackgr2 (wetting-in time for wire 2)
Vsc_thrsh2 [Volts]	short-circuit detection threshold voltage for wire 2
Varc_thrsh2 [Volts]	arc initiation detection threshold voltage for wire 2
WFR2 [m/min]	Feeding rate for wire 2

Table 4.15: List of parameters common to both wires in the TandemOptarc1

Parameter [units]	Summarized description and/or purpose
General parameters	
WFR_creep [m/min]	Creep wire feed rate

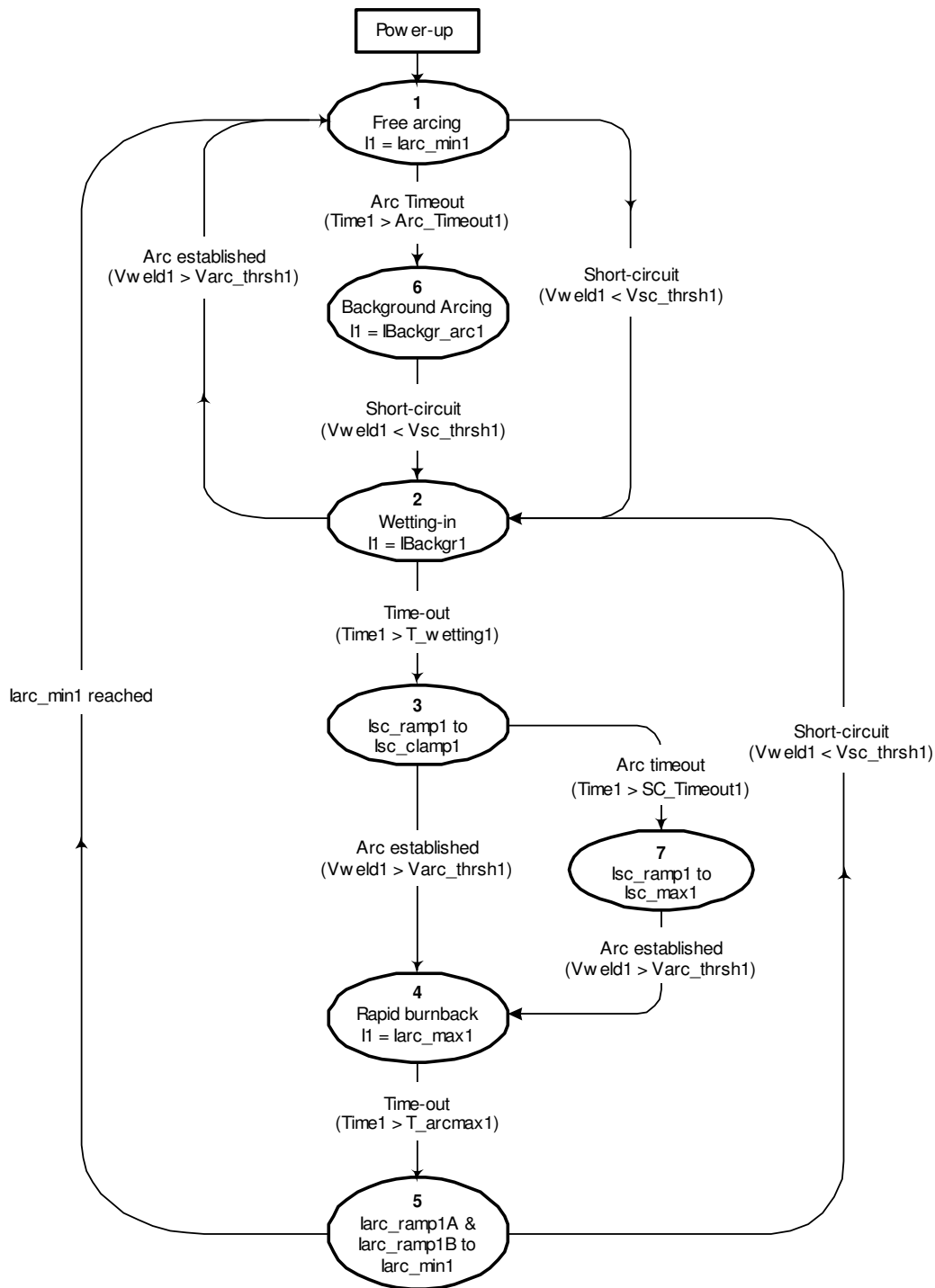


Figure 4.51: Control state diagram for the TandemOptarc program (wire 1)

Referring to Figure 4.49, the initiation of a short-circuiting event (state 2) is detected by the controller when the voltage drops below the short-circuit detection threshold Vsc_thrsh1 . For satisfactory process control, the delay in power source response between the actual start of short circuit and the voltage detection should not exceed 0.15 ms, and is preferably 0.10 ms or less (DEAN, 2003). The welding current reference is reduced to the background

current level $I_{backgr1}$. This promotes wetting of the molten droplet at the end of the electrode onto the welding pool, and reduces the risk of pool and droplet repulsion. Depending on the output inductance of the power source and the welding circuit resistance, the actual welding current will tend to “lag behind” the reference waveform during this state. If arcing is re-established in state 2, then the current is returned to the nominal arcing level (I_{arc_min1}). This ensures continued droplet growth and workpiece heating, as the short circuit was only an incipient one.

However, if the short circuit is successful, the end of the electrode “wets in” to the weld pool and material is transferred to the weld pool by surface tension. A predetermined time $T_{wetting1}$ must expire before the transition is made to state 3, when the current is again increased. If a droplet is repulsed during this period and an arc is re-established, the process goes to weld state 4 ($V_{weld1} > V_{arc_thrsh1}$). In state 3, the current is raised at the specified rate I_{sc_ramp1} (A/ms) to the specified short-circuit current clamping level I_{sc_clamp1} . A significant electromagnetic pinch force is exerted on the short-circuiting metal bridge to increase the rate of metal transfer. This weld control state is allowed to persist for the time $SC_Timeout1$. Parameters I_{sc_clamp1} and $SC_Timeout1$ are chosen in such a way that the short-circuit transfer is completed within $SC_Timeout1$, and I_{sc_clamp1} is selected to minimise spattering whilst maintaining process stability and a reasonably rapid short-circuiting period.

As shown in Figure 4.49, if the short circuiting does not terminate within $SC_Timeout1$, the controller moves to state 7. The welding current is increased at the rate I_{sc_ramp1} to the maximum short-circuiting current I_{sc_max1} . The current is held at this level indefinitely until the short circuit ruptures and an arc is re-established. This is an abnormal welding condition where process stability has been lost. Control state 7 is used to return the process back to a stable operating point, and avoid prolonged stubbing of the electrode into the weld pool. As shown in Figure 4.50, for a stable weld, the short circuit ruptures during the state 3, the voltage exceeds V_{arc_thrsh1} and the controller moves to state 4 ($V_{weld1} > V_{arc_thrsh1}$). The duration of states 3 and 7 is determined by the behaviour of the welding process.

In state 4, the arc is established after a short-circuit rupture, so a high, fixed current I_{arc_max1} is applied for the specified time T_{arc_max1} . This promotes weld pool depression and rapid melting of the electrode so that sufficient arc length is generated to avoid premature short circuit. The presence of a suitable arc length at the end of this state also ensures an arcing period of acceptable duration, so that the workpiece will receive adequate heat input for good fusion.

The only exit condition for state 4 is the expiry of the time T_{arc_max1} . If a short circuit occurs during this state, it is considered to be a fault condition. If a premature short circuit

occurs, the process goes to weld state 2. In practice, short circuit occurs only if $larc_max1$ is too low for the welding conditions. The values of $larc_max1$ and $Tarc_max1$ determine the arc length that is achieved at the end of this state and the droplet growth at the electrode tip. During state 5, the current is linearly reduced to steady state value $larc_min1$ at the two specified ramping rates $larc_ramp1A$ and $larc_ramp1B$ (A/ms). The ramp rate is set to $larc_ramp1A$ while the current reference is higher than the median value of $larc_max1$ and $larc_min1$. After this, the ramp rate is reduced to $larc_ramp1B$. State 5 is terminated when $larc_min1$ is reached, or a short-circuiting event occurs (refer to Figure 4.51). Again, this event is a fault condition, which occurs if $larc_max1$ is set too low. If no fault occurs, the duration of state 5 is determined by $larc_max1$, $larc_min1$, $larc_ramp1A$ and $larc_ramp1B$. This state (5) works as the tail-out parameter in the STT[®] process.

State 1 is the steady state free arcing period, where the current is kept constant at $larc_min1$. In almost all welding conditions it is the state with the longest duration. During this state there is significant droplet growth and the greatest heat input to the workpiece occurs. The current $larc_min1$ is constant and independent of the arcing voltage, so the rate of droplet formation is not affected by arcing conditions. As for states 3 and 7, the duration of this state is determined by the process behaviour. For a normal welding (Figure 4.54), state 1 ends when the droplet makes contact with the weld pool, so that the voltage drops below threshold Vsc_thrsh1 ($Vweld1 < Vsc_thrsh1$). However, if the arcing period is excessively long and exceeds $Arc_Timeout1$, the controller enters in state 6 (Figure 4.49). In this state, the current is immediately reduced to the background arc level $lbackgr_arc1$. This minimises the melting rate and promotes the onset of the next short circuit. State 6 ends and state 2 begins when a short-circuit occurrence is detected.

This approach for controlled short-circuit transfer provides a technique for regulating the current flow during short circuiting without dependence on short-circuit rupture premonition detection or rapid current reduction.

The interface of the program was based in the FlexTandem - Pulsed 1 interface, basically featuring the same facilities for data loading and saving, parameters setting, etc. Figure 4.52 shows the TandemOptarc - Version 1 interface/screen. Besides of having an amicable user interface (all parameters can be seen in one screen only, the parameters setting is facilitated, etc.), this program allows setting different parameters for wire 1 and 2 (important as two different power sources are employed and this feature allows operating with different wires – different parameters – for example). Examples of parameters file and data logging file used in the TandemOptarc program are showed in Appendix 4. The control program (DSP) is programmed in high level C language.

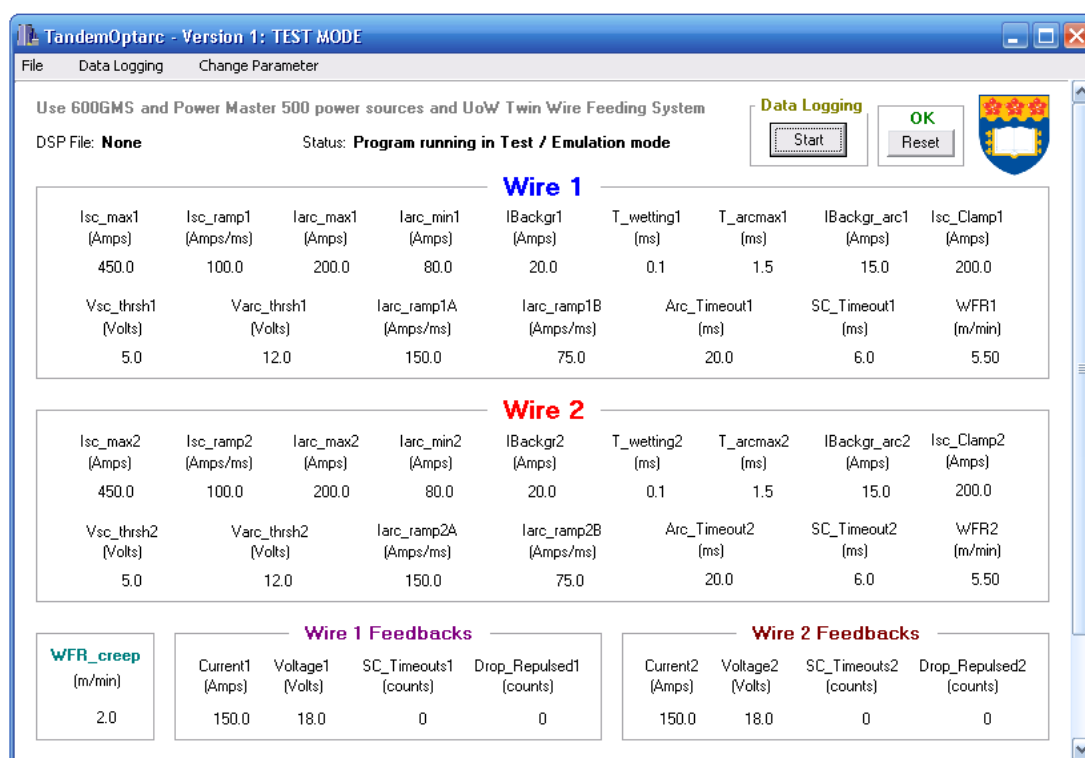


Figure 4.52: TandemOptarc - Version 1 program screen

Electrical feedbacks

In order to allow a real time checking of the current and voltage values and also some extra information, feedback values were provided in the TandemOptarc program (Figure 4.53). It is possible to check the instantaneous current and voltage for both wires, the number of times the process expires the maximum short-circuiting times (SC_Timeouts1 and SC_Timeouts2) and if any droplet repulsion occurs (Drop_Repulsed1 and Drop_Repulsed2).

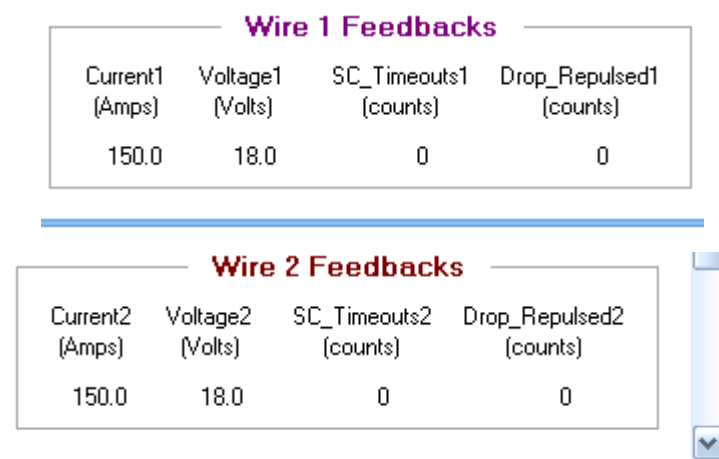


Figure 4.53: Feedbacks values provided by the TandemOptarc program

As weld spattering in short-circuit GMAW is generated at the instant of the droplet to weld pool short circuiting or at the re-establishment of the arc with the molten bridge rupture, these later feedbacks were devised to help in identifying the reasons for spattering in the process. For each wire if the arc is re-established within the first 0.72 ms (observed by Dean (2003)) of the short-circuiting period it means that spattering occurred due to droplet repulsion (beginning of short circuiting) and the related Drop_Repulsed feedback is incremented. If the short-circuiting limit time (SC_Timeout) (observed by Dean (2003) as being 5 ms for Ar and 23% of CO₂ and 6 ms for CO₂ for a wire of 0.9 mm in diameter) is achieved it means that spattering occurred in reason of molten bridge explosion (current rises to I_{sc_max} value at the end of short circuiting) and the associated SC_Timeouts feedback is incremented. The reset button showed previously in Figure 4.52 resets the SC_Timeouts and the Drop_Repulsed values to zero, which must be done before each weld to avoid considering the events of the last 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).

4.3.3 First trials using the TandemOptarc - Version 1 program

In order to verify the program operation, some 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 using the power sources. A reasonable combination of parameters was selected and data acquisition system was used to record the current and voltage signals from both wires. Figures 4.54 and 4.55 show the current and voltage transient signals with different current clamp levels for each wire (different waveforms). Figure 4.56 shows the current and voltage signals for wire 1 when a long arcing period and a long short-circuiting period are detected.

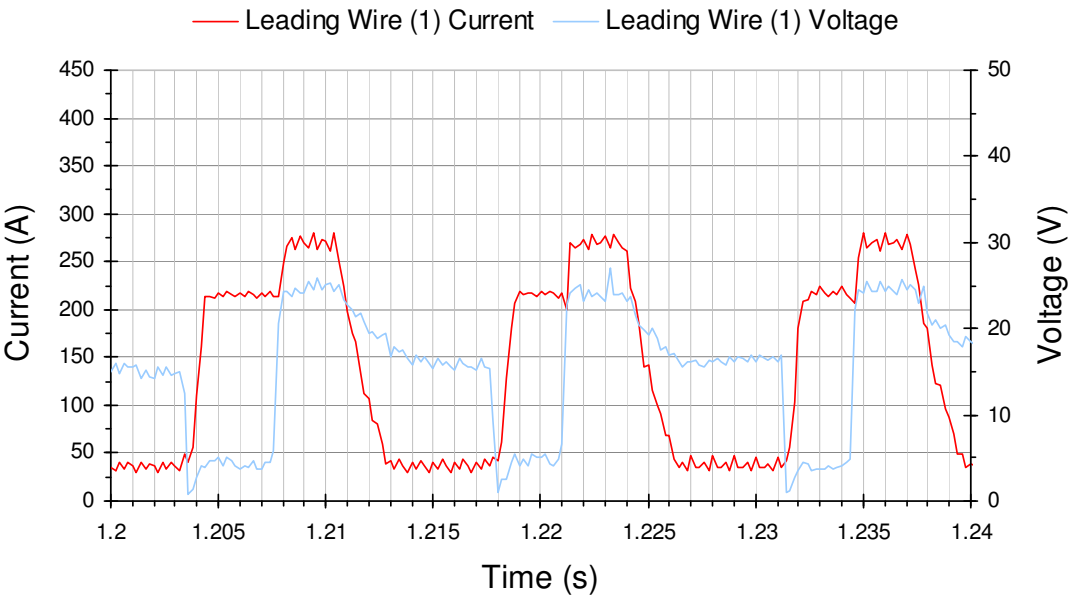


Figure 4.54: Current and voltage transient signals of the leading wire

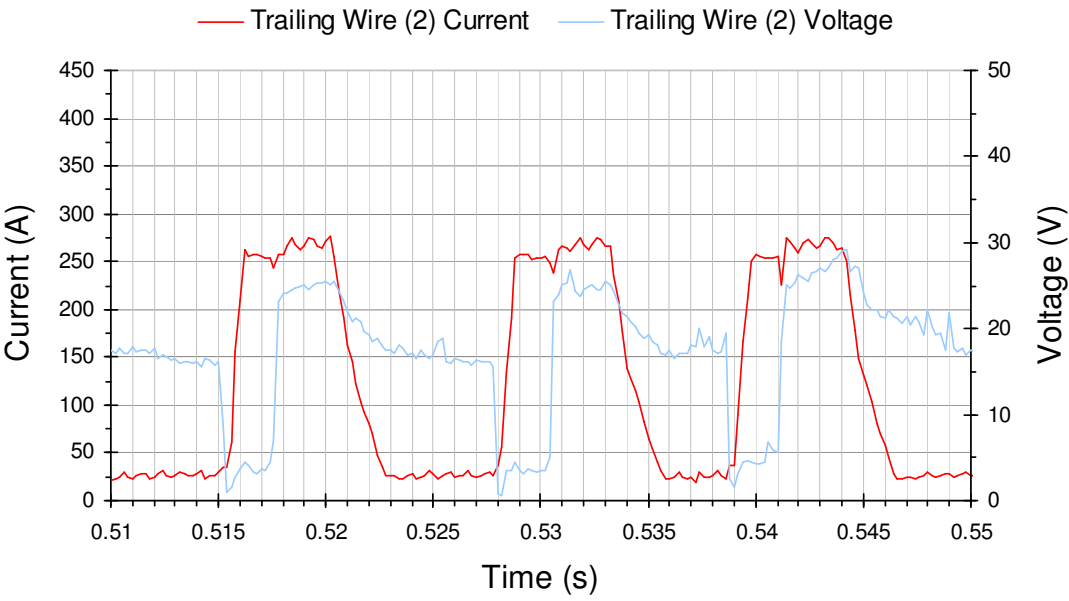


Figure 4.55: Current and voltage transient signals of the trailing wire

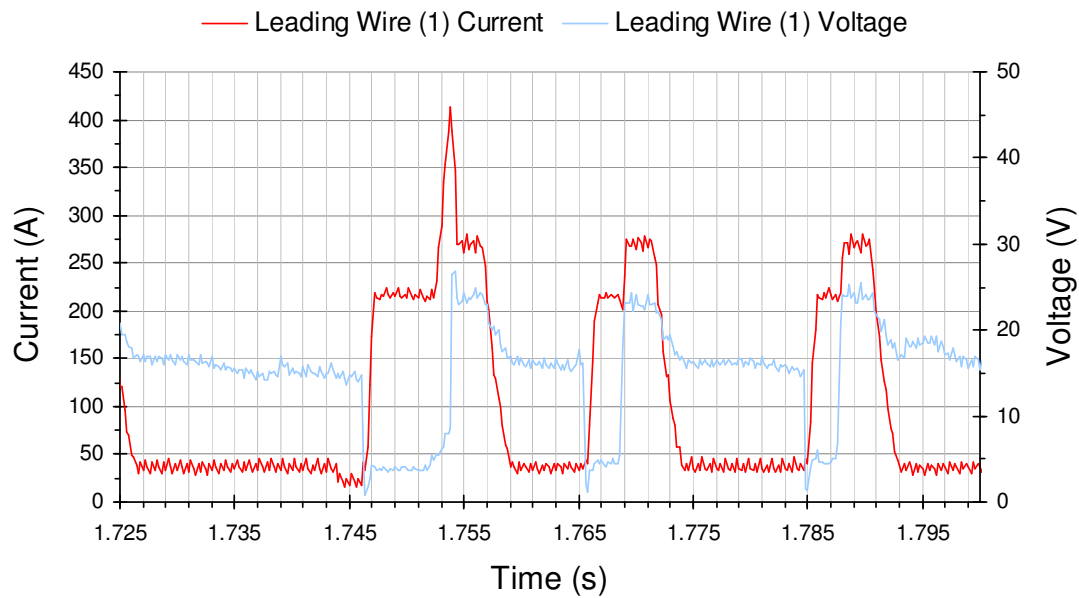


Figure 4.56: Example of current and voltage signals of the leading wire when fault conditions are detected

4.3.4 General comments

The first version of the TandemOptarc program was devised for controlled short-circuit tandem GMAW and presents an amicable user interface and high flexibility for parameters setting (independence between wires). The program was totally able to control the parameters (current waveform) for both wires.

4.4 Assessing the Tandem GMAW with Controlled Short Circuit Mode

During the first exploratory trials using controlled short circuit in both wires the process showed high level of instability, especially in the trailing wire. As a means of assessing the process and its feasibility, a series of tests was carried out. Initially the process was evaluated for single wire configurations (leading wire (wire 1) by itself and trailing wire (wire 2) by itself). After the insight in the performance of single wire welding, tests were carried out using the tandem configuration. A short circuit stability index was utilised as a reference to the process performance and high-speed video synchronised with transient electrical data was used as an auxiliary tool for process assessment.

4.4.1 Experimental conditions

For all wire configurations the welding travel speed was varied keeping all other welding parameters constant. The welding travel speed was varied in an attempt to modify the characteristics (size and shape) of the weld pool and to observe how the process would respond to these modifications. Five travel speed levels were used for single wire configuration and three in the case of the tandem arrangement. The travel speed values were selected to provide situations ranging from full penetration (imminent burn-through) to high travel speed (imminent humping). Five weldments were produced for each one of the conditions with the stability index standard deviation as a measure of repeatability of the outcomes.

The angles used for each wire for the single wire configuration were the same as for the tandem arrangement (Figure 4.57). As a consequence, in the single wire configuration the leading wire was tested 'trailing' the weld pool and the trailing wire tested 'pushing' the weld pool. Tables 4.16 and 4.17 show the welding parameters used. A shielding gas more suitable for the short-circuit welding mode was used. The welding sample and the method of fixing it to the welding table used were as it was described previously (Figures 4.23 and 4.24). The stability index defined previously by Eq. (2.1) was used to represent the stability of the condition and was calculated based in 2 seconds of acquisition for each weldment. High-speed video synchronised with electrical transient data was also taken for each condition.

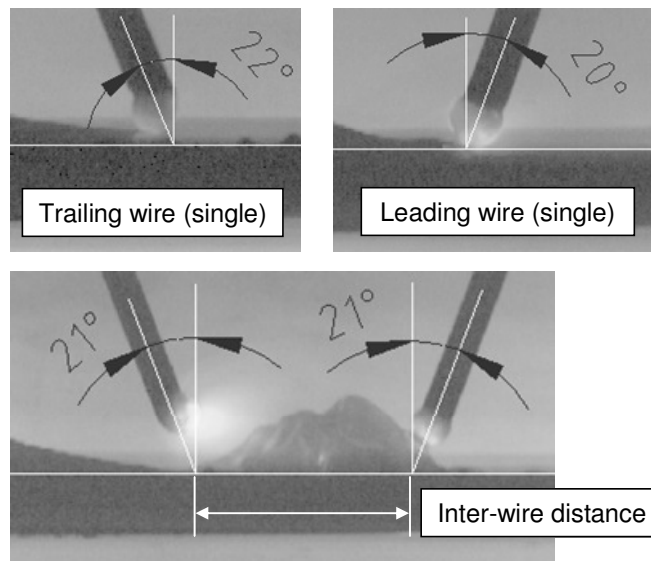


Figure 4.57: Electrode angles measured for single (top) and tandem configurations (bottom) and inter-wire distance parameter (trailing wire on the left and leading on the right)

Table 4.16: Parameters used for wires 1 and 2 throughout the tests

Parameters for Wire 1	Value	Parameters for Wire 2	Value
Isc_ramp1 [A/ms]	300.0	Isc_ramp2 [A/ms]	300.0
Isc_Clamp1 [A]	250.0	Isc_Clamp2 [A]	250.0
SC_Timeout1 [ms]	6.0	SC_Timeout2 [ms]	6.0
Isc_max1 [A]	400.0	Isc_max2 [A]	400.0
Iarc_max1 [A]	270.0	Iarc_max2 [A]	270.0
T_arcmax1 [ms]	2.5	T_arcmax2 [ms]	2.5
Iarc_ramp1A [A/ms]	150.0	Iarc_ramp2A [A/ms]	150.0
Iarc_ramp1B [A/ms]	75.0	Iarc_ramp2B [A/ms]	75.0
Iarc_min1 [A]	30.0	Iarc_min2 [A]	30.0
Arc_Timeout1 [ms]	20.0	Arc_Timeout2 [ms]	20.0
IBackgr_arc1 [A]	15.0	IBackgr_arc2 [A]	15.0
IBackgr1 [A]	20.0	IBackgr2 [A]	20.0
T_wetting1 [ms]	0.1	T_wetting2 [ms]	0.1
Vsc_thrsh1 [Volts]	5.0	Vsc_thrsh2 [Volts]	5.0
Varc_thrsh1 [Volts]	20.0	Varc_thrsh2 [Volts]	20.0
WFR1 [m/min]	4.00	WFR2 [m/min]	4.00

Table 4.17: Additional welding parameters

Welding Parameter	Value
CTWD* (both wires) (mm)	12
Inter-Wire Distance (mm)	10
Shielding Gas [81.25% Ar + 16% CO ₂ + 2.75% O ₂] (l/min)	35
Wires diameter [AWS ER 70S-6] (mm)	1.2
Inter-wire Angle (°)	42

* The CTWD parameter was considered as the vertical distance measured from the contact-tip to the workpiece

4.4.2 Using the leading wire or the trailing wire in single configuration

Table 4.18 shows the travel speed levels used and the results for the stability index, voltage and current for the leading wire (wire 1) whilst Figure 4.58 shows the relationship between welding travel speed and stability index for this wire. This relationship can be reasonably expressed as linear and the stability index decreased as the travel speed was increased. It is worth saying that the stability index is a statistical parameter and a more accurate relationship would require a great number of tests (replications) and with long time of acquisitions. The objective here was just to have a general idea on the behaviour of the process for different weld pool sizes.

Table 4.18: Stability index, voltage and current for wire 1 (single wire configuration)

WTS (mm/min)	Mean Stability Index	Stability Index Standard Deviation	Mean Current (A)	Mean Voltage (V)
357	0.82	0.0098	111.2	17.51
537	0.81	0.0183	112.6	17.83
717	0.75	0.0327	117.7	17.24
898	0.69	0.0248	114.6	17.08
1078	0.65	0.0667	115.1	16.51

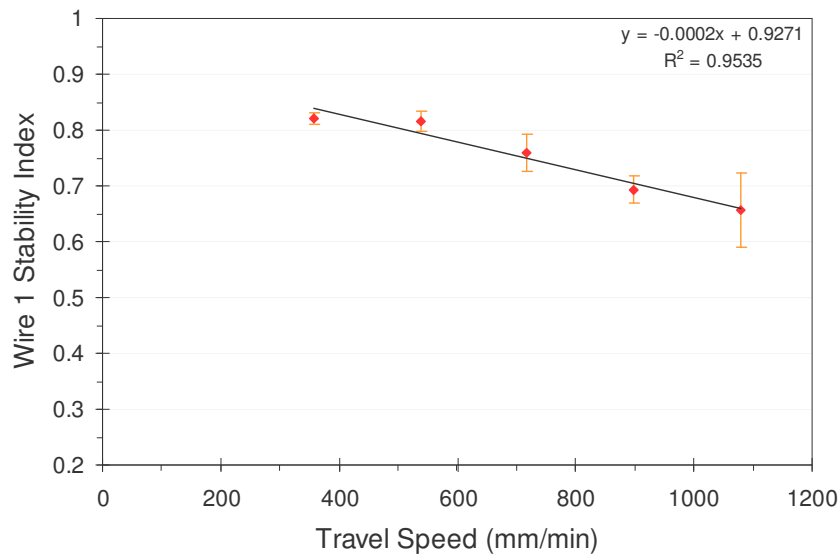


Figure 4.58: Relationship between welding travel speed and stability index for wire 1 (single wire configuration)

From the high speed-videos it was possible to see that for the lowest level of travel speed the weld pool was very 'flat' under the electrode, which meant a stability index determined basically by the wire fusion rate. In this case the pool oscillation was not enough to make the mass of molten metal move towards the droplet at the tip of the wire. In the case of higher travel speeds, it seems that the stability index starts to get more influence from the weld pool oscillation. Figure 4.59 shows how the weld pool changed from a flat surface under the electrode at the moment of short circuiting into a mass of molten metal moving towards the droplet as the travel speed was increased.

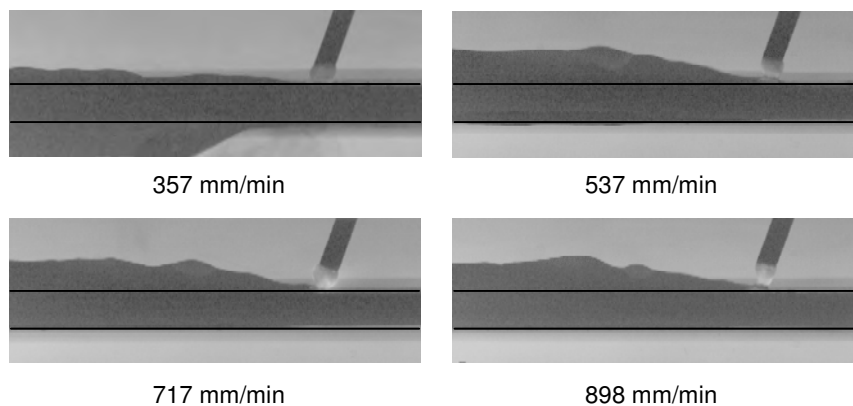


Figure 4.59: Welding process profile for different travel speeds 0.2 ms before the short circuiting event in wire 1 (single configuration)

Despite the decline in the stability index observed with the travel speed increase, perhaps the most important phenomenon verified was the amount of molten metal displaced by the pulse of current after the short circuiting event. Figure 4.60 illustrates how the weld pool is pushed backwards by the current pulse (the weld pool moved like a wave). Since the magnitude of the molten metal waves caused by the pulse of current is considerably higher than that presented by the waves from the pool oscillation, they can represent a serious threat for the stability of the second wire in the case of tandem wire configuration. Figure 4.61 shows a series of process images synchronised with the respective transient electrical data. Despite being controlled by current levels and times, the short circuiting event has yet a freedom regarding its frequency, which would make any attempt to synchronise the shorts between the wires very difficult. If compared to the pulsed process, it can be said that in short circuit mode the frequency of metal transfer is an output (consequence of all parameters and pool behaviour), whilst for pulsed mode the frequency of metal transfer is an input (set through the pulse parameters).

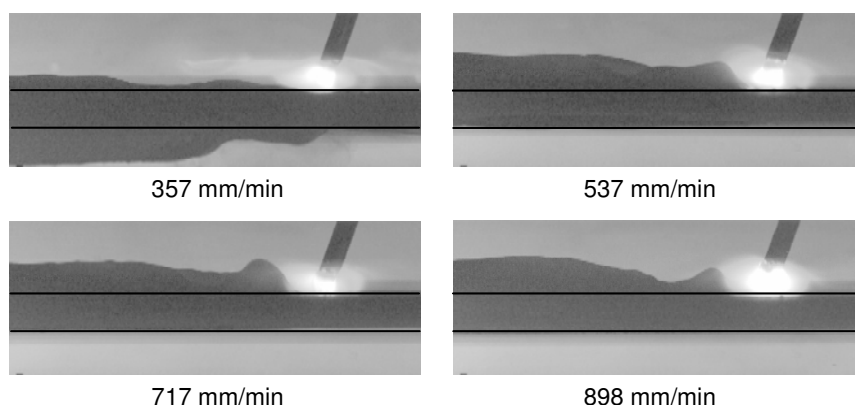


Figure 4.60: Welding process profile for different travel speeds 4 ms after the start of pulse in wire 1 (single configuration)

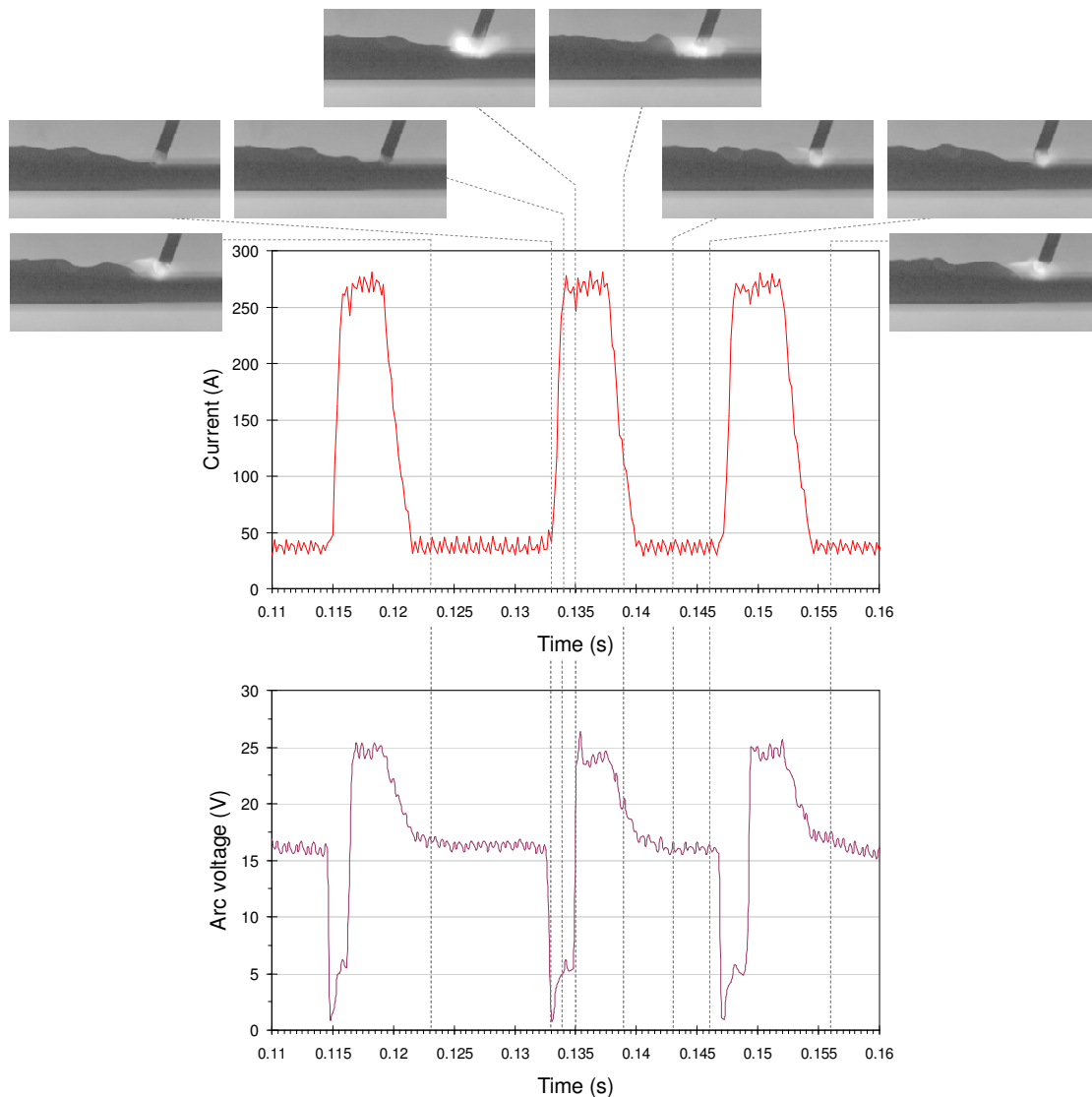


Figure 4.61: Process images synchronised with transient electrical data for wire 1
(single configuration at a travel speed of 717 mm/min)

An attempt to determine the weld pool oscillation frequency was made by applying fast-Fourier transformation (FFT) algorithm to the voltage signals from extra files (4 s of acquisition) and also through direct time measurements from the high speed videos. None of the methods allowed identification of the pool oscillation frequency. In the case of the FFT method, only peaks of frequency around the frequency of short circuiting were more defined. In the case of the videos, the movement of molten metal after the pulse of current made any attempt to determine the frequency of pool oscillation impracticable.

Table 4.19 shows the travel speed levels used and the results for the stability index, voltage and current for the trailing wire (wire 2). Figure 4.62 shows the relationship between welding travel speed and stability index for this wire. This relationship cannot be expressed as linear as it happened for the leading wire. For the lowest level of travel speed the stability

was high, since the weld pool under the electrode remained flat. For 537 mm/min the stability index sharply decreased. From the high-speed video it was possible to see that the weld pool assumed a different shape compared to that from the leading wire under the same conditions (Figure 4.61). It seems that in the case of the leading wire, as the arc is pointed backwards it pushes the molten material making the concentration of material in the pool more distant from the electrode. In the case of the trailing wire, as the arc is pointed forwards, the concentration of molten metal stays right behind the electrode, which increases the risk of random contact between the droplet and the pool, reducing the stability index (sometimes the contact even happened on the side of the droplet and sometimes the pool just missed the droplet in the tip of the electrode, as shown by Figure 4.63, which made the short circuiting period inconsistent).

Table 4.19: Stability index, voltage and current for wire 2 (single wire configuration)

WTS (mm/min)	Mean Stability Index	Stability Index Standard Deviation	Mean Current (A)	Mean Voltage (V)
357	0.74	0.0279	110.9	16.61
537	0.62	0.0383	111.2	16.86
717	0.74	0.0320	111.9	16.53
898	0.69	0.0261	113.7	16.12
1078	0.38	0.1043	117.9	15.42

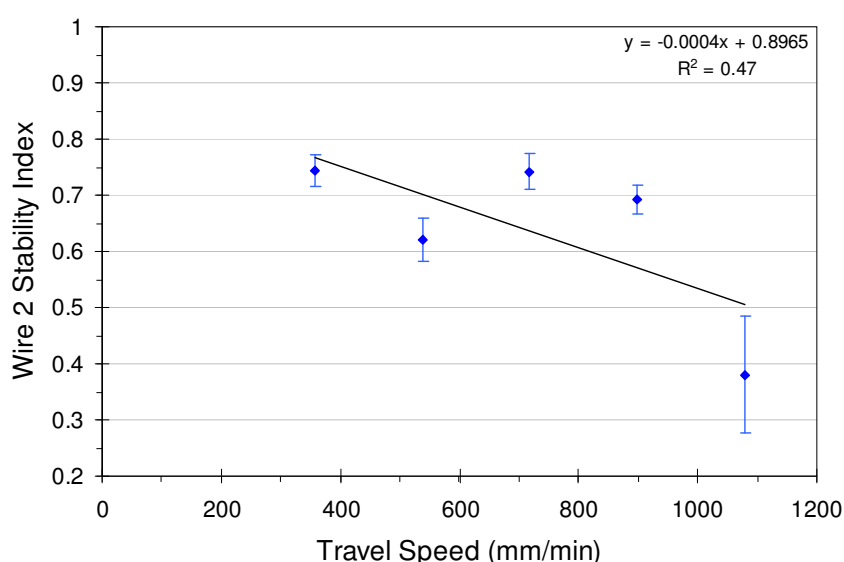


Figure 4.62: Relationship between welding travel speed and stability index for wire 2 (single wire configuration)

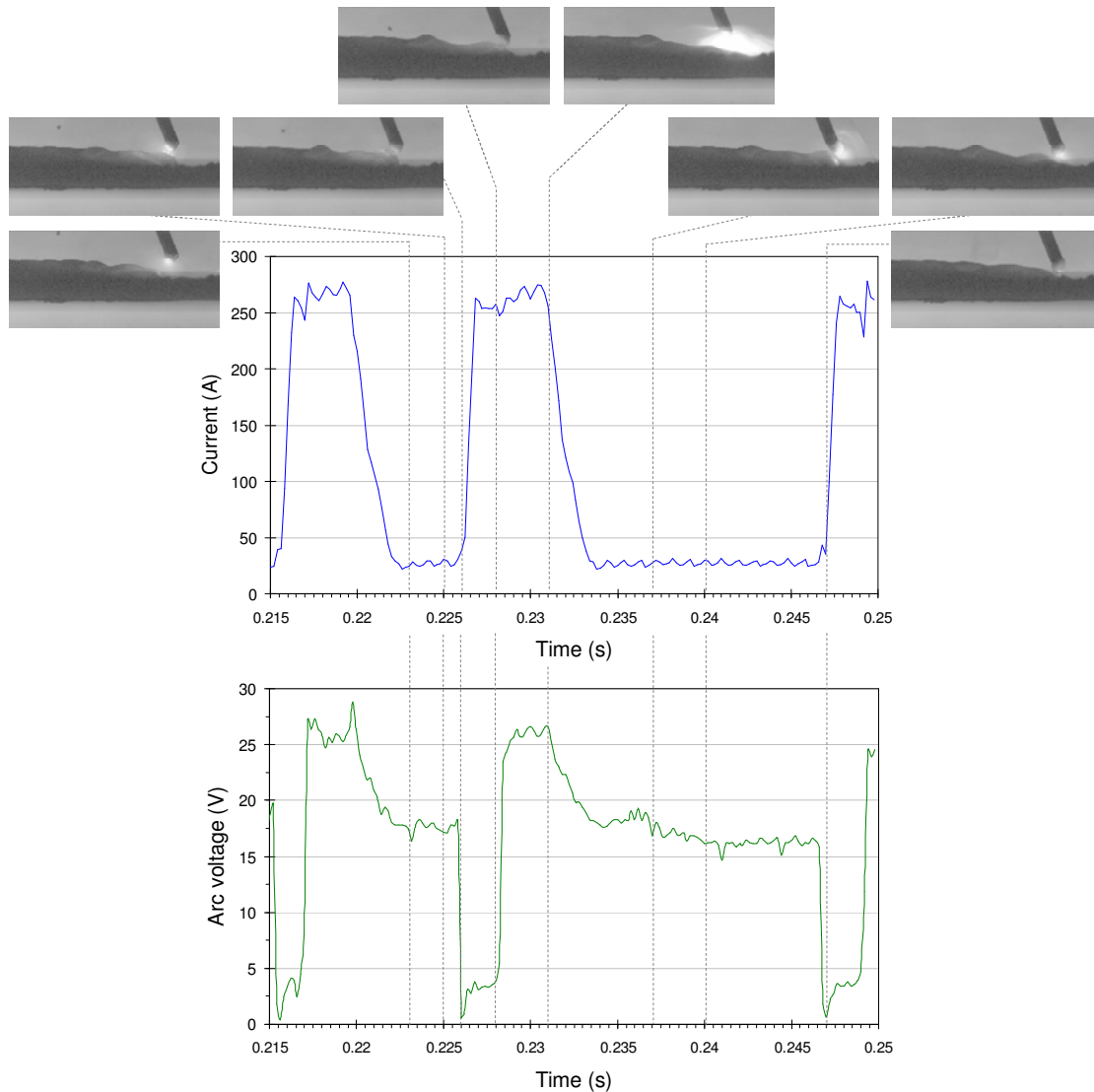


Figure 4.63: Process images synchronised with transient electrical data for wire 2
(single configuration at a travel speed of 537 mm/min)

For the next two levels of travel speed tried the stability index was similar to the index found for the leading wire when using the same conditions. For these speeds the weld pool assumed a very similar shape to that in the case of the leading wire (contact regularly under the droplet as it is illustrated by Figure 4.64). As the arc is pointed forwards, it seems that it is leaving the weld pool behind and, with it, the concentration of molten metal. At the highest level of travel speed, as it happened for the leading wire, the process was very close to the humping condition, which produced a stability index with high standard deviation. Any major assumption is difficult to be considered at this level of speed.