OPTIMIZATION OF
METAL TRANSFER AND FUSION
USING
CURRENT CONTROL
IN DIP TRANSFER GMAW

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University of Wollongong

Thesis Declaration

This is to certify that I, Gary Dean, being a candidate for the degree of Doctor of Philosophy, am fully aware of the University of Wollongong’s rules and procedures relating to the preparation, submission, retention and use of higher degree theses, and its policy on intellectual property.

I declare that the work reported in this thesis is my own, except where explicitly specified and referenced. I further declare that this thesis has not been submitted for a degree at any other university or institution.

Signed:

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Abstract

This research sets out to explore the mass and thermal transfer mechanisms involved in gas metal arc welding. This analysis was undertaken to enable improved process control strategies to be developed and evaluated.

As a result of the investigations a new current control approach is proposed for dip transfer GMAW for use with conventional primary inverter power sources. This new control approach offers improved spatter reduction and fusion control compared to conventional constant voltage control systems. The control approach is based on the premise that if optimum droplet transfer conditions exist, then the short circuit current can be minimized through clamping, the droplet transfer taking place primarily under the influence of surface tension. Unlike previous controlled dip transfer strategies this approach places no reliance on pre-emptive detection of the short circuit rupture or on rapid peak current reduction.

Novel adaptive control and monitoring techniques have been developed to assist in assessing the degree to which current clamping is introduced to the process, as well as identifying the type and degree of spatter generated. A study of optimized welding conditions has identified a relationship of use for the selection of welding parameters. The study led to the derivation of a hypothesis that defines the optimum short-circuiting event for droplet transfer. The investigation of the welding process has also identified inherent process irregularities when using CO₂ shielding gas, which has led to the development of control strategies whose actions minimize the affect and enhance the welding process stability.

To validate the proposed control approach a DSP based power source controller was designed and built. A comprehensive experimental program gave quantitative indication of the benefits likely to be achieved in practical welding situations.
Publications, Reports and Patents

Due to the commercial interest in this work from the financial contributors to this project, there has been a restriction on the publishing of details of this thesis. The internal reports, publications and patents arising from the work carried out for this project are as follows:

Publications


Internal Reports

Patents


Glossary of Terms

GMAW
Gas metal arc welding. Also referred to as metal inert gas welding (MIG).

Matlab
An interactive system and programming language for general scientific and technical computation.

DSP
Digital signal processor. A type of micro-controller which is suitable for high processing speed applications.

Meniscus
The curved surface of the molten bridge linking the droplet to the weld pool.

Wetting-in Period
The initial phase of the droplet bridge transfer where the droplet and weld pool coalesce (form as one).

Ar-23%CO₂ Shielding Gas
Argon based GMAW shielding gas mixture. Contents comprises 77% Argon and 23% CO₂.

Thermadyne
A manufacturer and supplier of welding equipment and consumables.

Average Cycle Arcing Current
The value of arcing current when time averaged over the dip transfer cycle (short circuit and arcing period).
Dip Transfer GMAW
A GMAW process which is characterized by a repeated short-circuiting and arcing cycle.

WFR
Wire feed rate. The feeding rate of the electrode wire during the welding process.

CTWD
Contact tip to work-piece distance. The distance between the end of the contact tip and the work-piece.

TWI
An internationally recognized independent research and technology organization for welding and associated technologies based in the UK.
2-1

Chapter 2
Short Circuit Droplet Transfer

2.1 Introduction
The principle objective in any welding process is to control the heat input for a desired level of fusion while achieving minimal weld spatter and surface degradation. Dip transfer gas metal arc welding is generally recognized as a procedure prone to spatter, and is characterized by the regular short-circuiting nature of the welding process. This Chapter considers the dip transfer process and in particular the process and control methodologies that distinguish it from other operating modes in regards to droplet transfer, weld spatter and fusion control.

Heat input, weld pool oscillation and short circuit droplet transfer each have a significant influence on process stability and spatter generation. These process characteristics and the mechanisms of spatter generation are reviewed to demonstrate the importance of using a holistic approach to dip transfer control. A brief overview of power source development is included and improvements in spatter and fusion control achieved through the evolution of power source technology are described. The limitations of conventional power sources in controlling the dip transfer process are also discussed.

2.2 Short Circuit Droplet Transfer
Metal transfer in GMAW is dependent on the balance of forces acting on the metal droplet with the principal forces being gravitational, aerodynamic drag, electromagnetic, surface tension and vapour jet. In the case of dip transfer GMAW, surface tension and electromagnetic forces appear the dominant forces, with the other forces considered small by comparison [1].

Early metal transfer research focused on the stability of an incompressible, electrically conducting fluid cylinder. From this work Murty [2] derived an equation for the interior pressure of a conducting incompressible liquid cylinder at a distance \( r \leq R \) from the axis, which is expressed as

\[
P = \frac{\gamma}{R} + \left( \frac{\mu_0 I^2}{4 \pi^2 R^2} \right) \left( 1 - \frac{r^2}{R^2} \right)
\]  

(2.1)
where $\gamma$ is defined as the surface tension, $\mu_0$ is the permeability of free space, $r$ is the radial distance and $R$ is the radius of the conductor. Allum [3] later extended Murty's [2, 4] analysis to incorporate the case of a viscous liquid cylinder carrying a surface charge to

$$P_0 (r) = \frac{\gamma}{R} + \frac{\mu_0 J_o^2}{4} (R^2 - r^2) - f_{EO}$$  \hspace{1cm} (2.2)$$

where $J_o$ is defined as the current density, $f_{EO}$ is an electric field stress which is considered to vary with changes in surface charge density due to surface deformation.

More recently analysis has been directed specifically at the short circuit droplet to weld pool bridging transfer using both numerical [5, 6, 7] and analytical techniques [8, 9, 10]. This has led to a comprehensive compilation of data with regards to the bridging break-up interval for varying current and droplet dimension, highlighting the balance of the dominant forces evident in the transfer process. The resultant transfer mechanisms are discussed in the next Section.

### 2.2.1 Droplet Geometry

The droplet geometry significantly impacts on the dominant force balance during the transfer process. A small droplet will tend to form a stable meniscus between the electrode and the weld pool with the influence of surface tension insufficient to solely promote the transfer. However according to Bless [11] once the droplet acquires a critical size, surface tension forces will solely promote the transfer. Both conditions are illustrated in Figure 2.1.

**Figure 2.1. Droplet geometry and transfer conditions**

An alternative analysis by Kiyohara, Okada and Yamamoto [12] refers to a critical liquid column length. For a liquid column less than the critical length the bridge
breakage is inhibited; however once the liquid column exceeds the critical length the bridge abruptly constricts to become thinner and breaks. Based on the assumption the column is a conical trapezoid, the following equation was derived to estimate the critical length for a known electrode and current flow.

\[ L_b = \frac{4 \gamma R^2}{\alpha I^2} \]  

(2.3)

where \( L_b \) is the threshold length, \( \alpha \) is a constant, \( \gamma \) is the coefficient of surface tension, \( R \) is the radius of the electrode and \( I \) the current flow. According to the equation the critical length is inversely proportional to the square of the current; however it can be seen that the equation will fail at low levels of short circuit current. Bless [11] suggests a critical height for weld metal drops will, in general, be greater than the wire diameter. Therefore it appears surface tension alone cannot account for the droplet transfer in short circuit welding if the mean droplet height is considerably less than the wire diameter.

From an analysis of transferring mercury and aqueous solution droplets Bless [11] derived an equation that estimates the droplet to weld pool transfer time as a function of surface tension and droplet mass.

\[ T_k = k \sqrt{\frac{M}{4 \pi \gamma}} \]  

(2.4)

where \( k \) is defined as a constant and \( M \) the droplet mass. The equation implies that the critical sized droplet will transfer to the weld pool in the minimum time, with increased transfer times anticipated with corresponding increases in droplet mass. The basic assumption of this equation is supported by numerical analysis of the short-circuiting droplet [7] with changes in droplet volume. This relationship is illustrated in Figure 2.2.
The analysis accentuates the relationship between drop volume, transfer time and the pinch radius and verifies theoretically the relationship between the break-up time and droplet volume. Conversely the break-up time is significantly influenced by the short circuit current flow as shown in Figure 2.3, where the break-up time for various levels of current is plotted for a constant droplet volume.

Initially capillary pressure is the dominant transfer force, with the influence of the electromagnetic pinch force more evident later in the transfer process where a current flow of 300A is seen to significantly reduce the break-up time [5, 7].
In summary it would be expected that surface tension can solely promote the droplet transfer once the droplet acquires a critical size, with the break-up time conditional on the droplet’s volume. However if a small droplet forms a stable meniscus a current flow would be required to promote the transfer, the magnitude of which is dependent on the length of the bridge.

2.3 Weld Pool Oscillation
Weld pool oscillation is a dominant feature of short-circuiting welding and a major factor in regards to the welding process stability [13]. The weld pool when excited into motion will exhibit natural frequencies of oscillation [14]; this excitation in dip transfer GMAW results from the transferring droplet's momentum at the molten bridge rupture [15] and the generation of arc pressure following the re-ignition of the arc. According to Lancaster [16] spatter minimization for dip transfer GMAW is realized by forming the bridge as close to the electrode axis as possible, and synchronizing the current frequency of oscillation with the natural oscillation frequency of the weld pool surface.

Weld pool oscillation behaviour has been studied extensively in the case of gas tungsten arc welding (GTAW) [17, 18, 19, 20, 14]. Kotecki, Cheever and Howden [17] reported the presence of weld pool oscillations while investigating ripple formation during the solidification of GTA spot welds. Renwick and Richardson [14] using a linear constant current power source measured the arc voltage ripple to determine the weld pool oscillation frequency for a stationary weld pool. They discovered the oscillation frequency was strongly dependent on the weld pool geometry, which correlated well with the inverse of the square root of the pool mass. Alternatively Deam [20] estimated the oscillation frequency by measuring the radiated arc light, which is proportional to the arc length, except at very low currents. Sorensen and Eager [18] developed a theoretical model for a stationary weld pool, which incorporated weld pool size, shape, density and surface tension, which they validated against the resonant natural frequency of the weld pool, derived from the voltage and current spectra using Fourier transform techniques.

For welding applications involving GTAW using a filler wire addition for interrupted bridging transfer [21] or dip transfer GMAW an estimation of the oscillation frequency from arc voltage measurements is difficult due to the effects of droplet growth, wire
feed rate, arc wander and changing contact tip resistance. Therefore attention has been directed towards identifying a correlation between weld pool characteristics and process statistical data in an attempt to derive the weld pool oscillation frequency. According to Hermanns, Spikes and den Ouden [13, 22] the maximal process stability is achieved when the short-circuiting frequency \((f_s)\) and the oscillation frequency of the weld pool \((f_{osc})\) are synchronized such that the short-circuiting frequency equals the oscillation frequency of the pool. Alternatively process statistical data has been utilized as a tool for detecting the partial to full weld penetration transition [23]. However even though the use of process statistical data is valuable in identifying the synchronization between the short circuit frequency and some weld pool characteristics, it is questionable whether this approach is appropriate for deriving the weld pool oscillation frequency in dip transfer GMAW. This relationship between the short-circuiting and weld pool oscillation frequencies is discussed in more detail in Chapter 5.

Xiao and den Ouden who have reported some of the most comprehensive work on this subject determined the natural oscillation frequency of a stationary GTA weld pool from the monitored arc voltage [19], and later using high speed filming identified the various phases of the oscillation modes that exist for weld pools with partial or full penetration, excited by stationary or travelling arc sources [24]. The three most common oscillation modes identified are shown in Figure 2.4.

![Figure 2.4. Common weld pool oscillation modes (From [25])](image)

For partial weld penetration, mode 1 oscillation is characterized by a relatively high oscillation frequency compared to mode 2 where the oscillation frequency is lower for a given weld pool geometry. In contrast, full weld penetration tends to generate mode 3 oscillation where the entire weld pool surface oscillates at a low characteristic frequency [24]. For a partially penetrated weld pool with a symmetrically located arc, the pool oscillation (mode 1) can be expressed in the following form as a function of weld pool geometry, surface tension and density of the liquid metal [26]
where \( D \) is defined as the diameter of the circular weld pool. For a travelling arc, the partially penetrated weld pool is elongated in the direction of travel and may demonstrate oscillation characteristics typical of either mode 1 or 2 depending on the symmetrical or asymmetrical location of the arc with respect to the weld pool [25]. The characteristic mode 2 oscillation captured on film [24] is illustrated in Figure 2.5.

\[
f_{osc} = 5.84 \sqrt{\frac{\gamma}{\rho}} D^{-3/2} \tag{2.5}
\]

The pressure pulse surface depression is represented by images (a) – (i), while the weld pool oscillation after the pressure pulse is represented by images (j)-(x). For elongated weld pools, it is appropriate to use an equivalent diameter \( D_e \) in calculating the oscillation frequency [25], which can be expressed in the following form for mode 2 oscillation [19].

\[
f_{osc} = 3.374 \sqrt{\frac{\gamma}{\rho}} D_e^{-3/2} \tag{2.6}
\]

where \( D_e \) is defined as the diameter of a circle with the equivalent surface area to that of the weld pool. If as reported the synchronization of the weld pool oscillation and short circuit has an impact on the welding process stability and spatter, then the weld pool oscillation may be expected to have a significant influence on the transfer behaviour in dip transfer GMAW.
2.4 Heat Input
Control of the heat transfer rate per unit length of weld is an important feature of fusion welding. Within the welding cycle, heat is delivered to the work-piece by several mechanisms. During the arcing phase heat is transferred from the arc column through convection, radiation and conduction, with energy also transferred through electronic phenomena in the cathode region [27]. By comparison the energy transfer during the short circuit period arises from the heat developed in the filler wire. While electrical energy is consumed during this period, it is generally in the form of resistive heating, most of which is believed to contribute to preheating the electrode wire extension [28].

An increase in heat input can be achieved in a number of ways, in particular by varying the mean current or increasing the CO₂ content of the shielding gas [29]. However excessive heat input to the weld can produce undesirable conditions in the heat affected zone (HAZ); depending on the material composition, tensile strength may be reduced, grain growth may take place and the width of the HAZ [30] and distortion may increase. Conversely on thicker plate increased heat input may be desirable to increase fusion, reduce cooling rates and prevent the formation of brittle HAZ phases.

2.4.1 Fusion Characteristics
Generally the weld fusion area may be divided into two main regions. "Primary Penetration" which is characterised by substantial penetration at the centre of the fusion zone and "Secondary Penetration" caused by comparatively slow melting at the edges of the weld pool [31]. The penetration region profile for a bead on plate or closed butt weld is shown in Figure 2.6.

![Figure 2.6. Weld bead and fusion profile](image)

The shape of the primary penetration profile is influenced by the contribution of the superheated liquid droplet transferred from the filler metal and the shielding gases composition, which for CO₂ shielding gases produces a wider and less finger like
shaped profile due to the wider droplet contact region, and less pronounced axial pressure compared to argon based shielding gases.

The secondary penetration by contrast is dependent on fluid flow and to a lesser extent the weld pool edges being heated by the outer regions of the arc plasma. Arc heating is found to significantly influence the bead width and sidewall fusion [27, 31]. Based on this observation techniques have been developed for controlling the weld bead geometry through surface temperature measurements [32].

### 2.4.2 Mechanisms Governing Fusion

The weld fusion area and depth of penetration are important quality criteria. It is well recognized that heat transfer to the work-piece has a significant influence on the width of the weld and the contact angle between the weld bead and the surface of the work-piece [27].

However, differences of opinion exist in regard to the mechanisms that most influence the weld penetration depth. According to Essers and Walter [27] a relationship exists between the momentum of the droplet impinging on the weld pool and the penetration depth. Even though heat transferred to the work-piece by the arc contributes about 75% of the total heat transferred to the work-piece, it is suggested by these authors that arc heat transfer has only a limited influence on the depth of penetration.

Murray and Scotti [33] suggest that the correlation between penetration depth and the momentum of droplets may only be applicable if the droplets carry sufficient momentum and energy and convey this energy to the base of the weld pool. It should be noted that a change in mass transfer at constant heat transfer might be accompanied by changes in current, voltage, arc length, mode of transfer, and the momentum and energy of droplets impinging on the weld pool. Therefore the depth of penetration may be affected by several physical variables that are related. This underscores the importance of a model, based on the assumption that the depth of the weld pool, heat transfer from the arc, and mass transfer due to droplets impinging on the weld pool may be correlated by a dimensionless relationship [33]. The expression for the model related penetration depth as a function of mass transfer, heat transfer and welding speed. From this work it was found that mass transfer affects the depth of penetration, although the effect of arc
heat transfer is more significant. The data tended to indicate that for free flight transfer with larger penetration depths, a strong correlation exists between depth and mass transfer. While for short arc transfer where penetration depths are considered low, arc heat transfer has a strong correlation to penetration depth. This is also expected for dip transfer since the droplet momentum is negligible.

A detailed heat balance by Allum and Quintino [34], based on a simple plate fusion model for pulsed GMAW using thermal conduction heat transfer for a moving point source, revealed that plate melting occurs largely due to arc heating, with only a small contribution from the droplet heat, depending on the relative pool and droplet temperature.

### 2.4.3 Calculation of Input Power

The heat transfer rate is an important variable in fusion welding since it governs heating rates, cooling rates and weld pool size. Generally the higher the heat input rate the lower the cooling rate and larger the weld pool. However some discrepancy exists with regard to the conventional calculation and directly measured values of weldment heat input for pulsed and dip transfer welding processes. Both of these transfer modes are characterized by complex voltage and current waveforms [35]. Bosworth [36] evaluated the mean power calculated as a function of the arithmetic mean voltage and current values against that derived from the summed instantaneous power for pulsed GMAW. The average power calculated as a function of the summed instantaneous power was found to offer the closest correlation to directly measured values of heat input. The validity of this approach was recently confirmed by Joseph and Harwig [37]. Therefore the mean power delivered to the arc can be expressed as

\[
P_{av} = \frac{1}{n} \sum_{i} v_{arc} (i) \times i_{arc} (i)
\]

where \(v_{arc}\) and \(i_{arc}\) is defined as the instantaneous arc voltage and current, and \(n\) the number of samples. To calculate the weldment heat transfer the mean arc power is directly substituted into the following equation [38]

\[
H_n = \eta_t \times \frac{P_{av}}{\nu}
\]

where \(\eta_t\) is the thermal efficiency and \(\nu\) is the welding travel speed in mm/s.
2.4.4 Heat Transfer Distribution

The welding process energy may be divided into three parts: that transferred to the electrode, due to the condensation of electrons and energy gained in passing through the anode drop zone; that radiated and convected from the arc column, and that transferred to the work-piece through electronic phenomenon in the cathode region and gas heating resulting from convected gas flow in the arc column [39]. This relationship is illustrated in Figure 2.7.

![Figure 2.7. Energy distribution in the welding process](image_url)

As shown for the consumable electrode welding processes, energy consumed by the melting electrode is later conveyed to the work-piece by way of the transferring droplet. Numerous studies have been carried out related to energy distribution within the welding process. Rosenthal [40] observed that for arc welding, less than 20% of the total arc energy was consumed in heating the solid part of the electrode, while losses due to radiation, vaporization etc. were roughly estimated to be 15% for small electrodes, leaving (for delivery to the work-piece) approximately 65% of the total arc energy. Jackson and Shrubsall [41] reported that for manual arc welding, approximately 14% of the total arc energy is consumed in melting the electrode, while only 16% of the total arc energy contributed to base metal melting with the remaining 70% of the total arc energy considered as heat loss resulting from plate heating, fusing coating, radiation, and convection. Watkins, Smartt and Einerson [42] investigating heat transfer in spray transfer GMAW, reported a total thermal transfer efficiency of 85%, with the arc energy accounting for 45% and droplet transfer 40% of the total input energy transferred to the work-piece.
This emphasizes the importance of calculating the work-piece energy transfer as a function of the welding process thermal transfer efficiency as it appears that not all the energy consumed by the welding process is transferred to the work-piece. The arc power should be calculated for pulsed or dip transfer welding using an average power derived from the summed instantaneous power to achieve the closest correlation to the directly measured heat input. The arc heat transfer it is believed has a significant influence on the weld fusion area and depth of penetration in dip transfer GMAW.

2.5 Spatter Formation in Dip Transfer Welding

It has been established that weld spatter in dip transfer GMAW is generated at the commencement and completion of the short circuit transfer period, and can be reduced by welding parameter optimization. The improved process stability is reflected in the statistical distribution of the voltage, current, short circuit and arcing periods [43], which has led to the development of statistical models for spatter estimation [44]. For conventional constant voltage (CV) control systems spatter reduction [45] and increased process stability [46] is usually achieved through the optimization of the voltage and the addition of series inductance into the welding circuit.

2.5.1 Spatter at the Instant of the Short Circuit

Spatter generated at the instant of the short circuit is usually the result of electromagnetic repulsion prior to or during the wetting-in of the droplet to the weld pool creating ball spatter. High-speed images captured at the instant of short-circuiting suggest the contact diameter to be less than 0.4mm [47]. The existence of high current at the instant of the short circuit for short arc pulsed GMAW has been reported to produce violent repulsion that prevented metal transfer [48]. The level of current that will initiate droplet repulsion can be related to the curvature of radius at the point of contact, which according to Lebedev et.al [49] is determined by the following equation

\[ I_w = \pi \sqrt{\frac{2 \gamma R_k}{\mu_o}} \]  

(2.9)

where \( I_w \) is the critical level of current, \( \gamma \) is the surface tension coefficient, and \( R_k \) the droplet curvature radius. The equation implies that higher levels of current are required with an increasing curvature radius to initiate droplet repulsion. However droplet growth alone may not necessitate an increasing curvature radius. Excess droplet growth
using a CO₂ shielding gas is detrimental to the transfer process, as the shape becomes irregular, with a tendency towards rotational movement and an inconsistency of curvature at the point of contact. A minimal contact area when combined with the rapid rise of current, which normally accompanies a short circuit, is therefore more likely to facilitate droplet repulsion.

2.5.2 Spatter due to Bridge Rupture
Due to the dynamic response of the conventional welding power source output under short circuit conditions, high current flow tends to exist at the instance of the molten bridge rupture. The peak current is reported to have a qualitative relationship with respect to the weld spatter generated during this period [50]. According to Zaruba [51] weld spatter generated during this event is a consequence of an electrical explosive force, and a direct relationship exists between metal spatter and the molten bridge’s explosive energy generated during the short circuit period [52]. This leads to the supposition that spatter can be reduced by lowering the short circuit current, by lowering the voltage drop in the bridge through shortening the bridge length or by minimizing the short circuit period.

A detailed analysis by Zaruba [51] has determined that the heat generated in the molten bridge is sufficient to vaporize the molten metal as it reaches a specific diameter. The analysis confirmed that the current density of the molten bridge at rupture was within the range to achieve an electrical explosion of the conductor. It is suggested that spatter suppression is achieved when the detection of precursory events at the commencement of short-circuiting and arc re-striking is accompanied by a reduction in current [53].

2.5.3 Spatter Formation in Coated Steel
From a metallurgical perspective the impact of the heat input on the weld thermal cycle and heat affected zone (HAZ) is of major interest in the welding process. However as spatter formation is exacerbated when GMAW is applied to zinc based coated steels, the importance of coated surface damage from the generated weld spatter and the weld bead porosity becomes more apparent when welding these materials.

Gregory and Herrschaft [54] reported that while welding galvanized-coated steel with dip transfer GMAW and CO₂ shielding, repulsive forces at the wire end appeared much
greater than for the case of uncoated steel welding. It was suggested that this may be due to the presence of vapour streaming that could be produced from the high vapour pressure metals that exist within the steel’s coating. Cooksey and Milner [55] have demonstrated that droplets from electrode materials of magnesium, zinc or cadmium had transfer characteristics that could be related to the vaporization effect of these metals in the arc. Using either electrode positive or negative polarity intense vaporization of the electrode material was reported which resulted in the repulsion of the molten drop from the base plate due to the back reaction thrust of the vapour stream. The droplets were transferred to the base plate some distance away from the point of arc impingement.

For the case where welding is performed on galvanized plate using a mild steel electrode, the vapour streaming is expected to result from the vaporization of the base plate zinc coating, which exerts a repulsive force at the end of the molten electrode wire. The influence of this force on the droplet prior to short-circuiting would appear to contribute to the increase in weld spatter [54]. Its impact however can be reduced by lowering the welding travel speed to promote zinc burn-off at the front of the weld pool. The degree of decrease is largely dependent on the zinc coating thickness, joint type and shielding position.

2.6 Dip Transfer Control Techniques

2.6.1 Constant Voltage Control

In dip transfer GMAW applications control of the filler-wire melting rate is generally a function of the mean current, which is dependent on the open-circuit voltage, wire feed rate and secondary inductance. The open-circuit voltage is related to the arc voltage and in conjunction with the wire feed rate determines the operating and maximum short circuit current flow. The secondary inductance controls the current rate of change and provides a mechanism for controlling weld spatter and plate fusion [56].

At the onset of the short circuit in dip transfer constant voltage (CV) control the current will increase at a rate governed by the welding circuit inductance. This rate must be sufficient to enable the molten bridge to "clear" and re-establish the arc [56]. For small values of inductance the current rise will be rapid, which results in high current and spatter at the molten bridge rupture. Conversely excessively high values of inductance
can cause arc failure during re-ignition or instability at low arcing currents [57]. An example of a transient voltage waveform typically produced when using a CV power source for dip transfer is illustrated in Figure 2.8.

![Figure 2.8. Constant voltage control waveform](image)

Conventional welding power sources using constant voltage control are designed to provide self-adjustment and stabilization of the arc length. The variations in arc length produce a significant converse change in the current and electrode burn-off behaviour. This counteracting response provides self-regulation [1] of the arc length to low frequency variations in contact tip to work distance (CTWD) [58].

Using CV control spatter is reduced by limiting the maximum current during the short circuit through the addition of inductance [45]. However this approach tends to decrease the short circuit to arcing period ratio [59] with the longer arcing period providing greater heat input, which may be beneficial in some circumstances but may make the process more difficult to control. Therefore the optimum inductance with some welding applications may depend upon factors other than spatter minimization [45].

### 2.6.2 De-coupled Control in Dip Transfer

Improved control of the dip transfer GMAW process is possible if the short circuit and arc heating stages can be de-coupled. This was realized as early as 1966 when Smith [60] developed a duplex welding power source system. This system consisted of two power supplies connected in parallel. A low voltage, high current CV power source provided the short circuit energy whilst a constant current supply provided the arc energy. The two supplies could be controlled independently to provide stable transfer and variable arc heating. More recently de-coupling of the short circuit and arcing periods has been attempted using constant voltage control techniques. Utilizing an electronic power source with independent control of the short circuit current rise and post short circuit current fall rates, some degree of de-coupling was achieved which
provided a higher regularity of metal transfer and a reduced incidence of incipient short circuits and weld spatter [61].

The rapid development in power electronic technology has made it possible to implement current control waveforms, which de-couple the welding process and offer greater control and regularity of the pulsed [62] and dip transfer GMAW process [63], with enhanced control of heat transfer and work-piece fusion compared to conventional CV control. The use of these control waveforms for dip transfer GMAW has been proposed by a number of authors [53, 57, 64, 65, 66, 67, 68], many of which have been applied to practical welding applications.

2.6.2.1 Power Source Development

In the mid 1970’s Boughton et.al at TWI [69] developed an alternative dip transfer control technique, which dynamically controlled the short circuit cycle using a sophisticated electronic power source. This offered improved molten droplet to weld pool wetting-in, significantly low levels of spatter, and accurately controlled fusion. Needham and Boughton [70] proposed a short circuit welding power source with fast current turnoff capabilities and detection circuitry, which sensed the impending rupture of the molten bridge. This power source, which is illustrated in Figure 2.9, was primarily intended for dip transfer welding. It comprised a DC power source for the sole purpose of supplying a restricted current to maintain the arc, and a second power source with minimal inductance that provides responsive current control during the short circuit period.

![Figure 2.9. Block diagram of the TWI power source. (From [70])](image)
Following on from this, a multi-function power source was developed for TIG and consumable electrode arc welding applications [71]. The basis of the design for dip transfer welding was to provide a method and device for controlling the power source, with the capability of rapid attenuation of the output current to suppress weld spatter to a minimum. This was accomplished by the insertion of an impedance element into the welding circuit upon the premonition sensing of the molten bridge rupture. Spatter reduction was achieved if the short circuit current was reduced to levels below 150 amps prior to the bridge rupture. The circuit of Figure 2.10 illustrates the parallel configuration of the switch (SWD) and impedance element (RA) utilized for rapid current reduction during the short circuit.

Later Parks and Stava [72, 73, 74] developed a purpose built power source for dip transfer welding utilizing a similar design concept for the primary welding circuit as proposed by Nakanishi et al [71] to achieve instantaneous current reduction during the short circuit period. The innovation of Stava's [74] design was based on the understanding that the arc can be re-ignited with a relatively low background current. Utilizing some of the concepts proposed by Needham and Boughton [70], a power source was employed that provided a continuous supply of background current. This used a primary welding circuit that contained a relatively low inductance (L1) in series with the premonition-switching network to ensure dynamic control of the current during the short circuit period. A simplified circuit diagram of the background and primary circuitry is shown in Figure 2.11.
An alternative power source topology [67] has been developed for robotic welding applications, which comprises an inverter stage on the primary and secondary of the power source transformer. This offers similar process control functionality as that described above. More recently a technique not dependent on premonition detection, but relying on the retraction of the wire during the short circuit has also been demonstrated using current control techniques [75, 76, 77, 78]. Even though mechanically more difficult to achieve, this technique also seeks to de-couple the short circuit transfer from the arc heating process.

Whilst the development of welding and power source systems has been pivotal to the advancement of welding technology, their potential has only been realized through their control methodology.

2.6.2.2 Development of Control Methodologies

The development of power source technology has been closely accompanied by corresponding developments in control methodologies. Boughton and Macgregor [64] reported significant process improvements to the wetting-in of the molten droplet by delaying the short circuit current pulse for typically 0.5ms. Spatter reduction was also achieved by terminating the current pulse prior to the molten bridge rupture. The proposed current control waveform [70] is illustrated in Figure 2.12.
It can be seen that the voltage and current remains relatively constant during the arcing period. With the onset of the short circuit, the current $i_2$ may be reduced to prevent repulsive ball spatter. After a wetting-in period the current $i_3$ is increased and maintained at that level for the majority of the short circuit period. The necking of the molten bridge will cause a significant increase in the voltage $v_3'$. The detection of the event ensures the current $i_4$ is lowered prior to the bridge rupture.

Ogasawara, Maruyama, Sato, Hida and Saito [79] who used a transistorized "inverter based" power source with small inductance [53] and Parks and Stava [72, 73, 74] using the specialized circuitry for rapid current response which was described earlier, have adopted control waveforms that subtly differ from that proposed by Needham and Boughton [70]. In each case a strong dependence is placed on premonition detection of the ensuing molten bridge rupture and a power source with substantially instantaneous current response capabilities under short-circuiting conditions.

For the control waveforms proposed by Maruyama et.al and Ogasawara et.al [67, 79] the welding current is maintained at a relatively low level upon the establishment of the short circuit. After a wetting-in period the current is increased to a relatively high level, before reducing to a low level upon the detection of the molten bridge necking. On re-establishment of the arc a pre-determined current pulse is applied to produce rapid droplet burn-back and weld pool depression, which significantly reduces the incidence of incipient short circuits [80]. The arcing current is subsequently reduced to a background level. A waveform of the control sequence proposed by Ogasawara et.al [79] is shown in Figure 2.13.
Figure 2.13. Current control waveform (From [79])

By comparison the control waveform proposed by Stava [74] follows a similar control sequence to that illustrated in Figure 2.13. The pinch pulse during the short circuit period comprises a double slope configuration, while the transition between the plasma boost and plasma stage is exponential in nature to minimize weld pool disturbances. This is illustrated in Figure 2.14.

Figure 2.14. Lincoln current control waveform (From [74])

Notable similarities between the control methodologies do exist, in particular with respect to their approach to short circuit control. This is emphasized by their dependence placed on a pinch mode to accelerate the metal transfer, the optimization of wetting-in conditions through the maintaining of low or reduced current during the initial short circuit period, and as discussed earlier, rapid current switching prior to the bridge rupture. Differences between the control methodologies are more evident with respect to their approach to arcing and electrode burn-back control. The control methodology adopted by Parks and Stava [73] is directed at controlling the droplet growth to a consistent size, usually to a diameter in the order of $1.5 \times$ that of the electrode. The control methodology adopted by Ogasawara et.al [79] focuses more on parameter selection to achieve optimum welding conditions.
2.6.3 Conventional Inverter Power Source

The topology of the "conventional" electronic inverter power source available for most welding applications is of the form illustrated in Figure 2.15. Using this design topology a smoother output and utilization of a physically smaller and lighter transformer and inductor is facilitated by increasing the primary switching frequency of the inverter power stage [81]. When applied to welding applications the technology provides the potential benefits of improved electrical efficiency [82], improved starting, improved arc stability and response, portability and ease of adaptation for multipurpose uses [83].

![Figure 2.15. Conventional Primary inverter power source](image)

This type of circuit was initially used for manual metal arc (MMA) power sources but is now employed for GTAW, pulsed GMAW [1] and dip transfer GMAW usually with constant voltage (CV) control. The utilization of current control methods for dip transfer GMAW based on this inverter design topology has been limited by the power source’s high level of circuit inductance, which impedes rapid current turn-off during short circuit conditions.

2.7 Summary

Surface tension and axial electromagnetic pinch forces significantly influence short circuit droplet transfer. It is suggested that a short-circuited droplet will transfer to the weld pool due to surface tension influences if the critical droplet size criteria is satisfied. Below the critical size a balance of surface tension and electromagnetic pinch forces are required to promote the transfer. Numerical and analytical modeling of the droplet transfer has accurately described the relationship of the transfer break-up time with respect to the droplet volume and current flow. There is general agreement that the break-up time will increase with decreasing current flow or increasing droplet volume.
Process stability in dip transfer GMAW is significantly influenced by the synchronization of the weld pool movement with the process short-circuiting frequency. This short-circuiting frequency can be easily attained from direct measurement of the process voltage and current signals. However, unlike the GTAW process, the measurement of the pool oscillation frequency from the arc voltage is difficult because of various process constraints. Therefore, attention has been directed towards identifying a correlation between weld characteristics and process statistical data in an attempt to derive the weld pool oscillation frequency.

The welding process energy is a function of the quantity transferred to the electrode, that radiated and convected from the arc column and the amount transferred to the work-piece. The control of the work-piece heat transfer rate is an important feature of fusion welding. However, a discrepancy exists with regard to the conventional calculation and measured value of work-piece heat input for pulsed and dip transfer welding, which are characterized by complex voltage and current waveforms. It has been found that the mean power derived from the summed instantaneous arc power offers the closest correlation to directly measured values of heat input when compared to the conventional calculation of mean power derived from the mean voltage and current.

Spatter generation in dip transfer welding occurs at the instant of short-circuiting and upon the molten bridge rupturing. In each instance, the generated spatter is a function of the current flow whether in the form of electromagnetic repulsive forces at the instant of short-circuiting or in the form of electrical explosive forces during the molten bridge rupture. Spatter suppression can therefore be achieved by maintaining low current during these occurrences.

Selection of control parameters for conventional constant voltage control in dip transfer GMAW is restricted due to the process coupling that exists between the short circuit and arcing period. With the development of inverter power sources, welding control processes have been directed at techniques that provide de-coupling of the short circuit and arcing period control functions. As a result, significant improvements to process control and weld spatter suppression have been achieved. This development has focused on power source systems with capabilities of significantly fast current control during the
short circuit period with a strong reliance on premonition detection of events to achieve the reported improvements.

As significant emphasis has been placed on the influence of the electromagnetic pinch force to achieve short circuit droplet transfer conventional inverter topology designs have been restricted to constant voltage control applications. It is however suggested that if dip transfer control is considered as a holistic process, then alternative control techniques may be adopted that provide process de-coupling of the short circuit and arcing period, and independent weld spatter and fusion control without a reliance on premonition detection and instantaneous short circuit current control. Such control techniques could operate within the constraints of the equipment design whilst still providing significant process benefits. A new control methodology designed to overcome the limitations described in this Chapter was devised and is outlined in Chapter 4. To aid the development of the new control methodology a study of weld pool oscillation characteristics and the synchronization between the weld pool oscillation and the short-circuiting event was carried out and is discussed in Chapter 5. An assessment of the control methodology and its ability to regulate heat input and fusion characteristics was performed, the details of this assessment are discussed in Chapter 6.
3.1 Introduction

In order to assess alternative control methods it was necessary to construct a power source control system that provided an adaptable environment to control and monitor the experimental procedure. The control system described here was designed and manufactured for the express purpose of developing alternative control techniques for dip transfer GMAW utilizing conventional primary inverter power sources. A brief description is also given of the test facility the control system was integrated with during this development and testing.

Photographic techniques have been found useful in providing alternative visual perspectives when evaluating and assessing the impact of different control techniques on the welding process. An outline is given of two photographic techniques that were utilized: a digital photographic system that uses frontlighting and a shadowgraph high-speed photographic system implemented specifically for this project. The result of this work is discussed in later Chapters.

3.2 Experimental Test Equipment

3.2.1 Description

The experimental system comprises four key sections: 1) A digital signal processor (DSP) based control system, 2) An operator interface, 3) A signal isolation unit and 4) The welding power source, wire feed unit and peripheral field devices.

The primary function of the DSP based control system is to control the welding process through the online execution of control algorithms, to perform process state monitoring and identification, and to control ancillary functions related to the exchanging of data between the operator interface and the DSP controller.

Control of the welding process is realized through the interfacing of analog and digital input and output (I/O) signals between the DSP based control system and field devices. The task of the field device will generally be to provide either a control or feedback function. The controlled devices for this system configuration include primarily the
welding power source and wire feed unit, with current and voltage feedback obtained from a current transducer and through direct measurement respectively. For process control the associated device signals are electrically isolated and scaled by the signal isolation unit before interfacing with the DSP controller. A simplified diagram of the experimental setup developed for this project is shown in Figure 3.1 with a more detailed schematic of the electrical interface provided in Figure A1.5 of Appendix 1.

![Figure 3.1. Schematic representation of the experimental setup](image)

As can be seen from the schematic drawing the DSP based control system is pivotal to the operation of the welding process. The physical layout of the control system and signal isolation unit identified in the schematic drawing is shown in Figure 3.2.

![Figure 3.2. Power source control system](image)

As can be seen the control system and signal isolation unit (right hand side box on the table in Figure 3.2(a)) has not only been designed for adaptability but also compactness and portability. The system setup is simplified by utilizing plugs and sockets in the
connection of field cabling to the isolation unit. An outline of the equipment that comprises the power source control system is given in the following sections along with a brief description of peripheral equipment associated with the test facility.

### 3.2.2 Welding Power Source

The interaction of the welding power source and wire feed unit with the associated control system forms the basis of the welding test facility. A custom-built, high-performance power source, developed for a previous project [84] was initially used to conduct research into the alternative control technique for dip transfer GMAW. An existing commercially available wire feed unit, which was modified for the same project, was also interfaced to the associated control equipment.

To evaluate the alternative control technique when applied to a conventional inverter power source the associated control system was interfaced to a commercially available primary inverter power source, suitable for both constant voltage and constant current welding processes. For dip transfer GMAW using the alternative control technique the power source was configured as follows: 1) the mode select switch was set to SMAW for constant current operation, 2) the arc force/inductance control was set to zero, 3) the output contactor switch was set to "off" and 4) the remote/local switch was set to "remote". While the function of the control system is to provide an external reference, some interfacing is always required between the power source and wire feed. A photograph of the conventional primary inverter power source is shown in Figure 3.3.

![Figure 3.3. A commercial power source interfaced to the control system](image)

Employing the front panel configuration described above the external reference can be used to control the power source current output during the welding process through the DSP controller. It was found that adequate current response could be achieved using this approach (refer to Figure 5.25).
3.2.3 DSP Control System

A commercially available digital signal processor (DSP) based controller board is housed within the tower case of the personnel computer (PC). The DSP comprises a 32 bit floating point processor which is programmed in the high level language “C” through the PC. A bank of DPRAM (Dual-Port RAM) provides a fast, continuous method for PC/DSP data exchange of downloaded target settings to the DSP and uploaded data to the PC. The data transfer is coordinated through a semaphore 'protocol' built into the DPRAM and the data transfer logic within the control program. A set of programmable registers provides the interface for control and status data exchange with the DSP [85].

Through embedded code stored in the on board EPROM (Erasable programmable ROM) the DSP functions in a stand-alone environment to provide real-time control of the welding process. The control program execution is interrupt driven at a rate of 25kHz (40μs period) by an external interrupt signal generated from the external digital I/O and interrupt board, which is connected to the digital I/O board via a 50 way ribbon cable. The electrical schematics of this are provided in Appendix 1, with Figure 3.4 illustrating a typical interrupt and program execution cycle.

![Figure 3.4. DSP interrupt and program execution cycle](image)

The controller has a digital I/O capacity of 16 inputs and outputs, which are TTL compatible and which can be either connected directly to equipment with comparable earthing or to field devices through opto-isolation. The inclusion of two ADC/DAC 16 bit daughter modules into the controller provides the control system with an analog capability of 4 inputs and outputs with an operating range of ± 3v, which require interfacing to the relevant field devices.
3.2.4 Signal Interfacing

Signal isolation is crucial to the interfacing of any form of electrical equipment, as the electrical potential of the ground reference for prospective interfaced equipment can differ significantly. To address this it was necessary to design and manufacture a signal isolation unit that provided the DSP controller I/O with electrical isolation from external field equipment. The following photographs show the front and back faceplate of the signal isolation unit, which was designed and built for this project.

![Front faceplate](image1.png)  ![Back faceplate](image2.png)

**Figure 3.5. Signal isolation unit faceplate layout**

The isolation unit comprises three interface boards (housed within a metal instrumentation enclosure) that provide analog reference and feedback signal isolation and scaling for the control system. The layout, which is illustrated in Figure 3.6, endeavours to maximize the segregation between power and control signal cabling to minimize induced signal noise.

![Layout](image3.png)

**Figure 3.6. Signal isolation unit layout**

Each isolation board has been designed as a standalone entity with both power supplies and isolation circuitry integrated into their respective boards, thereby requiring an AC mains supply along with the input and output signals.
For compatibility with Australian and US mains power supplies, each isolation board was designed and manufactured to operate on 240v 50Hz or 115v 60Hz AC mains power. The mains power supply is selected by a configurable link mounted on each isolation board, which electrically connects the dual primary windings of the power supply transformer in either a series or parallel arrangement. Erroneous power supply switch selections are avoided by mounting these links inside the isolation unit.

3.2.4.1 Reference Isolation
The reference isolation board contains two independent reference circuits, details of which are provided in Figure A1.7 of Appendix 1, that provide analog referencing for the welding power source and wire feed unit. The DSP analog output channel provides the input reference of ±0-3v, which is scaled to a ±0-10v output for the field device.

The circuit comprises three stages: 1) The voltage isolation between the DSP analog output channel and its associated field device is provided through a high common mode rejection isolation amplifier with dedicated DC power supplies ensuring the circuit isolation integrity, 2) the voltage scaling is provided through a differential-input amplifier with a high input impedance, low offset-voltage drift preamplifier stage and 3) the signal filtering which consists of a single pole 4.7μs RC network.

3.2.4.2 Current Feedback Isolation
A closed loop Hall-Effect current transducer located in the welding current return leg generates a current output of 0-100mA for a corresponding current of 0-500A. The transducer output current is initially converted to a corresponding 0-1v voltage by way of a 10 Ω resistor and a high impedance buffer amplifier at the input stage of the isolation circuit. A non-inverting amplifier stage provides the signal scaling to produce a 0-3v output for the DSP analog input channel. Any signal filtering is performed as required within the software. A detailed schematic diagram of this isolation circuit is found in Figure A1.9 of Appendix 1.

3.2.4.3 Voltage Feedback Isolation
The welding voltage was measured between the torch cable connection to the wire feed and the welding base plate and fed directly into the input of the voltage feedback
isolation board, where it is scaled from 0-75v to a 0-3v output for the DSP analog input channel. The voltage feedback is initially attenuated by a resistive network and then input to a buffered differential-input amplifier where the feedback signal is scaled for the specified output. Signal filtering of the voltage feedback is provided by a single pole RC network with a 40µs time constant to remove inverter induced switching noise from the signal. The detailed schematic diagram of the isolation circuit is shown in Figure A1.8 of Appendix 1. As the voltage feedback is critical to the detection of the short circuit and arcing period transition an analysis was performed to evaluate the impact filtering may have on the control process.

For this analysis the voltage feedback was obtained from the output of the feedback isolator with filtering disabled and captured using a storage oscilloscope. The measured power source voltage ripple for a mean voltage of 30v was found to be 4v with a ripple frequency of approximately 33kHz. At the re-establishment of the arc, the voltage rate of rise was estimated to be approximately 2000v/ms (this value may be higher as measurements may have been limited by the response characteristics of the isolation circuit) with an increase in voltage from 7-9v to 20-30v. When the feedback signal is superimposed on the filtered signal, a worst-case delay of 20µs is anticipated if a threshold voltage \( V_{arc-thres} \) of 12v is used to detect the short circuit to arcing period transition. Therefore the control action in response to this transition will occur within the next program execution cycle. The feedback signals associated with the welding process not only form the basis of the process control but also are crucial for data acquisition.

### 3.2.5 Data Acquisition

Data acquisition was achieved using two systems. The first was a customized data acquisition system developed at the University of Wollongong [86]. This system has been set up to monitor feedback data and supply statistical analysis of the welding process. The acquisition system has a sampling rate of 200µs per sample and generates a file of the voltage and current data that can be used later for further data analysis.

The principle data acquisition was provided by a digital storage oscilloscope with a 12 bit resolution and sampling rate up to 10MSa/sec. At a sampling rate of 20kSa/sec a 1
second period of welding data can be recorded and stored. The initiation of the oscilloscopes data acquisition was generated manually or through an event signal from the high-speed camera pulse generator unit. Stored data was then later analysed using customized software developed under a Matlab environment.

3.2.6 Software Control
The experimental control system was designed and manufactured for software configurable process control, which can function as a development tool for the alternative control technique, with the customized control software providing an adaptable environment for the development and evaluation.

3.2.6.1 Software Description of Current Control Dip Transfer
For control purposes the dip transfer process can be segmented into specific process states. For dip transfer GMAW key-state transitions occur with each re-establishment of the short circuit or arcing period, which are characterized in practice by rapid voltage excursions. In contrast sub-state transitions, which are dependent on the control methodology, occur during the period in between the key-state transitions and are usually instigated by specific time or control events. An example of the transition states and operator configurable parameters for a control waveform are shown in Figure 3.7, with $I_{sc\text{-}rmp}$ and $I_{arc\text{-}rmp}$ referring to the short circuit and arcing period ramp rates.

![Figure 3.7. Example of control waveform parameters](image)

The illustrated waveform accentuates the primary function of the process control system which is to control the weld process through the regulation of the welding current with
each state transition. The process control using state transition logic is discussed in more detail in later chapters. The scope and range of the control is largely dependent on the available operator interface.

3.2.7 Operator Interface

As stated earlier, the PC-based operator interface provides a medium through which configurable process parameters are transferred to the DSP controller, and conversely a medium for the controller to communicate process status and data to the operator. A typical operator screen layout design, which was developed and utilized for this project is shown in Figure 3.8.

<table>
<thead>
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<th>Version 1</th>
<th>Weld</th>
<th>Stopped</th>
</tr>
</thead>
<tbody>
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<td>Current</td>
<td>Voltage</td>
<td>Sp</td>
</tr>
<tr>
<td>1:1sec now 2:1sec-ns 3:1sec-emb 4:1sec-blk 5:1sec-min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>2000</td>
<td>500</td>
<td>2</td>
</tr>
<tr>
<td>2:1sec-ns 3:1sec-emb 4:1sec-blk 5:1sec-min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>200</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
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<td></td>
<td></td>
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</tr>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1:1sec-min 2:1sec-ns 3:1sec-emb 4:1sec-blk 5:1sec-min</td>
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<tr>
<td>150</td>
<td>75</td>
<td>20</td>
<td>6.0</td>
</tr>
<tr>
<td>2:1sec-min 3:1sec-emb 4:1sec-blk 5:1sec-min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>75</td>
<td>20</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Figure 3.8. PC-based Operator Interface

The operator interface screen outlines the process feedback data used in assessing the welding process along with the configurable process parameters utilized in the development of a control methodology. These parameters were easily modified through the selection of appropriate key commands and data entry. In summary the PC-based operator interface and the programmability of the DSP controller provide the power source control system with the flexibility desired when developing alternative control techniques for the welding process.
3.3 Ancillary Test Equipment

3.3.1 Experimental Welding Table
The welding table is a converted metal working lathe without the headstock. The lathe saddle forms a platform for the attachment of a welding base, with the lathe lead screw providing longitudinal travel [87], the speed and length of which is controlled through a variable speed drive (VSD) and programmable logic controller (PLC). A manually set potentiometer provides the VSD speed reference, while toggle switch selection presets the desired weld length, with the PLC terminating the welding process on achieving the target length. The work-piece is clamped to the welding base plate while the torch is fixed and secured to a support frame located above the welding table, and located approximately 500mm from the wire feed. The layout of the welding table and torch is shown in Figure 3.9.

![Figure 3.9. Layout of the Welding Table and Torch](image)

The physical configuration of the fixed welding torch with a moving table has a number of advantages. The most obvious is the ease with which photographic work can be performed.

3.3.2 Digital Photography
A Pulnix TMC-9700 progressive-scan CCD digital camera with its exposure externally synchronized to the DSP controller was utilized for the image capture of critical events during the welding process. Front lighting of the subject was provided by a high-powered xenon flash unit, which was synchronized with the digital camera. The layout of the photographic system used here but developed for a previous project [84] is shown in Figure 3.10.
The advantage of this approach is the CCD-based camera provides instant result evaluation (no film processing), full colour capability, exposure control synchronization to key events, low cost and front lighting of the subject which provides greater detail of the subject compared to shadowgraph photographic techniques.

3.3.3 High-Speed Filming

High-speed filming provides a convenient means by which to study the overall characteristic features of the dip transfer welding process. A high-speed photographic system using laser backlighting was implemented for the purpose of studying weld pool motion during the welding process. An advantage of this approach is the simple optical system of the shadowgraph technique significantly reduces the impact of the arc luminance that normally swamps the background illumination. This is achieved through interference filters, which were chosen to transmit wavelengths only within the range of the laser, while suppressing arc light outside the filter bandwidth [88].

Central to the photographic system is a Hadland Photonics Hypseed Camera using 16mm film, with a maximum filming speed of 10,000 frames/sec and a diode laser light source fitted with a telescopic lens which expands the collimated laser beam to a diameter of 15-20mm before projection onto the subject. After expansion the collimated light passes through the arc to an interference filter, which passes only the shadowgraph image of the electrode, droplet and weld pool that was generated by the laser backlight to the optics of the high-speed camera. The high-speed photographic system, which was developed for this project is illustrated in Figure 3.11.
The simple optical system comprises a 15mW diode laser source with a wavelength of 635nm, an adjustable telescopic lens for beam expansion and an interference filter having a wavelength of 635nm and a full width at half maximum (FWHM) transmission peak of 10nm. The filtered image was focused by a 200mm micro lens onto 16mm Tri-X reversal film at a filming speed of 4000 frames/sec. A photograph of the optical layout is shown in Figure 3.12.

The simple optical system which was implemented significantly reduces the setup time by requiring only one degree of alignment, while the detachment of the laser and high-speed camera from vibrating support frames ensure the integrity of the source and image. However irrespective of the optical quality of the photographic system and the captured film image the data extracted may prove worthless if not synchronized to recognizable events.

3.3.3.1 Event and Timing Pulse Generator

Incorporated into the Hadland Photonics Hyspeed Camera assembly are neon lamps used for event and time marking of the high-speed film. The lamps when energized transmit a source of light from the cameras latch block to produce a marking onto the outer region of the film.
A customized event and timing pulse generator was designed and built to provide remote start/stop camera control, event / time film marking and synchronization of the digital storage oscilloscope with the marked event. Detailed schematic diagrams of the pulse generator unit can be found in Figure A2.2 of Appendix 2.

The design of the event and timing pulse generator incorporates three distinct sections: 1) The pulse generator, 2) the high voltage driver and 3) the opto-isolation of the pulse generator and high voltage stage. The design of the timing pulse generator is based on an integrated circuit (IC) timer configured to function as an astable multi-vibrator and to operate as a free running pulse generator with a selectable frequency range of 100-1000 Hz. In contrast the design of the event pulse generator is based around a two IC timer network configured to function as a monostable multi-vibrator and operate as a single shot pulse generator. The output of either pulse generator provides the input logic to the high voltage driver circuitry through opto-isolation.

The design of the high voltage driver circuit was based on specifications of the outdated Hadland Photonics Hycam neon timing light generator. This supplied the neon lamp with a current of 14-90mA for a pulse width of 30 µs when filming at speeds of 650-11,000 frames/sec. For simplicity the relationship between the lamp current with respect to the film speed was assumed to be linear. For practical reasons a film speed of 4,000 frames/sec was chosen based on image resolution and the filming time available at the task speed for a 100ft reel. Therefore based on the above assumption a filming speed of 4,000 frames/sec will require an estimated current pulse of 35-40mA. The electrical parameters required to supply such a current pulse are determined by the following equation.

\[ I_{\text{lamp}} = \frac{V_{\text{supply}} - V_{\text{lamp}}}{R_{\text{limiter}}} \]  (3.1)

For this application, if a fixed high voltage supply of 360v DC is applied to a series connected 150v neon lamp and a 6.8kΩ current limiting resistor is used, then based on equation 3.1 the magnitude of the current pulse is 31mA. This is acceptably close to the estimated current required for a 4,000 frames/sec filming speed. The front and back faceplates of the pulse generator unit developed for this project are shown in Figure 3.13, while a layout of the control board and power supplies can be seen in Figure 3.14.
The photographic techniques employed have proven invaluable in the study of the weld process. The synchronization of the photographic image to recognizable events is crucial to the gathering of visual perspectives when evaluating and investigating the impact alternative control techniques have on the welding process.

### 3.4 Summary

A power source control system has been constructed for the purpose of developing alternative control techniques for dip transfer GMAW utilizing conventional primary inverter power sources. Central to the control system is a DSP based controller, which provides an adaptable environment for the development of such control methodologies. The evidence of this adaptable environment can be seen in the data exchange that exists between the operator interface and the DSP controller and the range of configurable process parameters available through the operator interface. However the control system's strongest adaptable feature resides in the programmability of the controller and the scope for control features, which can be implemented in a real-time environment.
The integration of the DSP controller into the control system required an interface to field devices that provided signal isolation and scaling. This was addressed by the manufacture of a signal isolation unit, which offers signal isolation and scaling for each of the reference and feedback signals required by the process. The unit when integrated with the PC and DSP controller forms an adaptable and compact control system.

To complement the control development work photographic techniques have proven invaluable for gathering visual perspectives when evaluating and assessing the impact of alternative control techniques on the welding process. A shadowgraph high-speed photographic system was implemented for this project and used in conjunction with an existing front-lit digital photographic system to produce alternative perspectives of process events.

Through the utilization of the power source control system an alternative approach for controlling the dip transfer weld process with conventional inverter power sources has been developed. Details of the approach and the control methodologies developed and implemented to enhance the control process are outlined in Chapter 4 & 5.
Chapter 4
An Alternative Control Technique for Dip Transfer GMAW

4.1 Introduction
The dip transfer gas metal arc welding process is characterized by the regular contact that occurs between the electrode and the molten weld pool, where the liquid droplet is transferred to the weld pool, and by the re-establishment of an arcing period.

This Chapter considers the control of dip transfer GMAW and in particular an alternative technique that can be applied to conventional inverter power sources for controlling the process. To facilitate the implementation of this alternative control approach it has been necessary to develop adaptive control and monitoring techniques. An overview of these techniques and the control enhancement and process evaluation they provide are discussed.

An analytical model of the droplet transfer has been developed and proven advantageous in demonstrating the impact the alternative control technique has on the transfer process and its usefulness in minimizing the short circuit current during the molten bridge rupture and its potential for weld spatter reduction. A description of the transfer model is provided and is verified against empirically derived transfer characteristics. The transfer model clearly demonstrates the current clamping methodology and its impact on the droplet transfer process. An assessment of the alternative control technique is also discussed, this examines the generated weld spatter, process stability and performance against alternative industry accepted dip transfer control techniques.

4.2 Basis of the Alternative Control Concept
As already stated in Chapter 2 significant enhancements to the dip transfer process have been realized through the development of process specific power sources using short circuit premonition detection. This has resulted in a control which de-couples the short circuit and arcing period and achieves significant reductions in weld spatter. However a need exists for the development of alternative control methodologies that provide these enhancements to the dip transfer process without a dependence on process specific power electronics. It is envisaged that the development of such methodologies will
require an approach with more emphasis directed towards the utilization of naturally inherent transfer forces, such as surface tension.

It is well documented that surface tension and electromagnetic pinch forces significantly influence the short circuit droplet transfer. According to Bless [11] a short-circuited droplet will naturally transfer to the pool under the sole influence of surface tension on condition that the droplet is above a critical size, with the droplet transfer time naturally expected to increase with droplet growth. However with regard to welding applications a limit to droplet growth is generally required due to the irregular and unstable nature of the process with excessive droplet size, which can potentially impact on wetting-in conditions and the droplet transfer. Conversely if the droplet is smaller than the critical size the transfer is inhibited by the formation of a stable meniscus, which must be overcome by a high electromagnetic pinch force to promote the transfer.

In practice the utilization of surface tension as a primary transfer force has been exploited for dip transfer and short pulse welding applications for some time. The dip transfer control methodologies proposed by Needham and Boughton, Stava and Ogasawara et.al [70, 74, 79] utilize a current controlled wetting-in period, which is initiated at the instance of the droplet to weld pool short circuit. Using this approach the current is reduced to a minimum to limit the likelihood of droplet repulsion. For each of the proposed methodologies, at the completion of the wetting-in period a high electromagnetic pinch force is introduced to assist the necking and rupture of the molten bridge.

Alternatively a control methodology has been developed for short pulse GMAW [80], which instantly lowers the current on the detection of the short circuit and thereby establishes surface tension as the primary mechanism to clear the short. If unsuccessful within a fixed delay time the control raises the current until the short circuit is cleared. Even though the control and reasoning behind clearing the short circuit may differ for each example the importance of the surface tension influence during the short circuit droplet transfer cannot be underestimated.
4.3 Alternative Control Approach

An alternative control approach has been developed in the present work for dip transfer GMAW. It is based on the premise that providing a critical sized droplet is developed prior to short-circuiting, surface tension can be utilized as the predominant droplet detachment force rather than the electromagnetic pinch mechanism. Fundamental to the alternative control technique is a short circuit current clamping methodology, which clamps the maximum short circuit current to levels lower than are normally encountered using conventional constant voltage control techniques. By utilizing such a methodology the short circuit droplet transfer should advance under the predominant influence of surface tension due to the limited electromagnetic pinch force.

However for practical reasons the transfer period must be completed within a desired time frame. Therefore the level the short circuit current can be lowered to will be essentially a function of the droplet geometry, surface tension, weld pool oscillation behaviour and the desired transfer period. This relationship is represented by the following function $f$ where:

$$I_{sc-clp} = f(\text{Droplet Geometry}, \gamma, f_{osc}, T_{sc})$$  (4.1)

The alternative control methodology like other dip transfer control techniques discussed in Chapter 2 endeavours to de-couple the control of the short circuit and arcing period. At the instance of short-circuiting, like the methodologies discussed in Section 2.6.2.2, the control reduces the current to promote the wetting-in of the droplet to the weld pool through surface tension. Then upon the completion of the wetting-in period the short circuit current is increased until it reaches the prescribed clamping level where it is maintained until the molten bridge ruptures, thus limiting the current flow at the instance of the bridge rupture, minimizing the electrical explosive forces and significantly reducing the weld spatter.

Upon the molten bridge rupturing the arc is re-established, the event accompanied by the application of a current pulse which depresses the weld pool and rapidly burns back the electrode wire to prevent any possibility of an incipient short circuit. By utilizing a current pulse during the arcing period aspects of pulsed GMAW theory can be applied to promote controlled droplet growth. According to [89] in dip transfer GMAW the
The highest rate of droplet growth occurs during the initial period of its formation, after which the growth continues at a much slower rate until eventually the droplet volume remains virtually constant until short-circuiting. Therefore, based on the following pulsed transfer detachment Equation 4.2, the droplet can be rapidly grown to a predetermined size.

\[ D = I_p^n t_p \]  

where D is defined as the detachment constant, I_p is the pulse current, n is a constant between 1.1-2 and t_p the pulse period. Following the droplet forming pulse, the current is reduced to a background arcing level to achieve the desired work-piece heat transfer. A schematic representation of the alternative current control waveform is illustrated in Figure 4.1.

**Figure 4.1. Alternative current control waveform**

The various stages of the proposed control waveform may be described as follows:
1) Prior to the short circuit (t_1), the current level is that stipulated for arc heating.
2) Upon short circuit detection (t_1), the current is reduced to facilitate the droplet's wetting-in to the weld pool (t_1→t_2).
3) On completion of the wetting-in period (t_2), the short circuit current is increased to the clamp level and held until the molten bridge ruptures.
4) Upon detecting the bridge rupture (t_3), a current pulse is applied (t_3→t_4) to depress the weld pool and grow the droplet. The predetermined pulse parameters achieve droplet growth without detachment.
5) An arc heating phase \((t_4 \rightarrow t_5)\) follows which is dependent on the specific level of arc heating, and is controlled independently of the short circuit transfer process.

Through the de-coupling of the dip transfer process the function of the alternative control approach is divided to control: 1) the droplet forming pulse and heat input during the arcing period and 2) the current clamp level during the short circuit period. However scope is still required within the control technique to deal with unexpected process disturbances. This has been addressed through the implementation of backup control strategies, which are discussed later in this Chapter.

This is unlike the control methodologies proposed by others [74, 79], which place strong dependence on premonition detection of the ensuing molten bridge rupture and a power source with substantially instantaneous current response capabilities under short-circuiting conditions. Instead the alternative control approach can be applied to most conventional inverter power sources since it requires only the detection of the rapid voltage rise on arc ignition and the rapid voltage drop at the commencement of the short circuit [90] to identify the arcing and short circuit periods. Hence the control methodology presented here provides a novel technique for regulating the current flow during the dip transfer short circuit period without dependence on short circuit rupture premonition detection, or rapid current reduction.

It is expected that modelling of the short circuit period using the alternative control current clamping methodology should provide some basis towards understanding the impact current clamping may have on the droplet transfer characteristics.

### 4.4 Modeling of the Drop Transfer

Central to the alternative current control technique is the limiting of the current during the short-circuited droplet transfer. An insight into the impact short circuit current clamping has on the transfer process can be readily gained through the development of a model which describes the short circuit current clamping levels that can be achieved for varying droplet volume.

In modelling the transfer process the geometry of the liquid metal surface around and below the electrode after short-circuiting is such that a rigorous analysis is only possible
using numerical solution techniques [16]. Such analyses of the droplet bridging transfer have been reported [5, 6, 7] which illustrate the bridging break-up time characteristic for variations in droplet volume and current flow. Alternatively, analytical models of the short circuit transfer have been developed. Ishchenko’s [8] model predicts the short circuit transfer time based on surface tension influences. Yan and Simpson [9] modelled the droplet transfer by approximating the liquid droplet as a truncated symmetrical sphere and utilizing the break-up time data of Hirata, Onda, Osamura and Ohji [91]. While another approach by Choi and Lee [10] estimates the bridging break-up time by calculating the volume of fluid transfer from the bridge to the molten pool through the contact region.

4.4.1 Model Design

For the purpose of this work, a rigorous analysis of the transfer process was not thought to be necessary. Therefore, an analytical approach that generates realistic outcomes was used to develop some insight into the transfer process. The model implemented for the droplet transfer analysis is based fundamentally on the approach adopted by Choi and Lee [10]. For this analysis, the bridge break-up time is estimated from the volume of fluid transfer through the contact region interface of the molten bridge and weld pool surface. The average pressure at the bridge centre defined by Equation 4.3 is expressed as a function of the surface tension and the mean electromagnetic pinch force.

$$P_{\text{ave}} = \frac{\mu_0 I^2}{8 \pi^2 R_1^2} + \gamma \left( \frac{1}{R_1} + \frac{1}{R_2} \right)$$  \hspace{1cm} (4.3)

where $\mu_0$ denotes the permeability of free space, $\gamma$ is the surface tension, $I$ is the current flow, $R_1$ is the inside radius, and $R_2$ the outside curvature of radius of the bridge as demonstrated by Figure 4.2.

![Figure 4.2. Molten bridge to weld pool interface](image)
The flow velocity at the contact region interface is calculated using the Bernoulli equation, with the flow velocity expressed as

\[ v = \sqrt{\frac{2}{\rho} \left( P_{ave} + \rho g h \right)} \]  \hspace{1cm} (4.4)

where \( \rho \) denotes the density of the molten metal, \( h \) is the distance between the contact region interface and the bridge centre, while \( g \) is gravity. If it is assumed the transferring fluid between the bridge and the pool is a function of the flow velocity, contact area and sampling interval. The displaced volume can be calculated using the following equation.

\[ V_{dis} = v \cdot A_c \cdot \Delta t \]  \hspace{1cm} (4.5)

where \( A_c \) denotes the area of the contact interface and \( \Delta t \) the sampling interval. An evaluation of the Choi and Lee [10] model reveals very low estimates for the bridging break-up time. This is believed to be due to the model's assumptions, which make no allowance for the formation of a meniscus during the wetting-in period. According to an observation by Bless [11] based on transferring mercury drops to a pool, within "the transfer process a meniscus is first formed which rises up to nearly the top of the drop and then falls". Therefore when modelling the transfer process some allowance should be made for the formation of a meniscus. The following diagram illustrates a simple meniscus formation.

![Meniscus formation with a transferring droplet](image)

**Figure 4.3. Meniscus formation with a transferring droplet**

The model developed here assumes that: (1) The initial phase of the droplet bridge transfer comprises a wetting-in period which encompasses the formation of a meniscus between the droplet and the weld pool, (2) The meniscus fluid forms part of the transferred volume, (3) The contact diameter between the bridge and pool surface is equal to the wire diameter, (4) The flow velocity within the bridge and pressure within the weld pool is neglected, (5) The bridge shape is described by two principal radii as illustrated by Figure 4.2, with the outside contour of the necking bridge sinusoidal in
nature, (6) The bridge gap decreases during the short circuit period due to the continued wire feed and (7) The pool surface remains flat with stable metal transfer. This model is evaluated in Section 4.7.2 after the further analysis of the control strategy in the following sections.

4.5 Ancillary Functions and Adaptive Control

To facilitate the implementation of the alternative control approach, adaptive control and monitoring techniques have been developed that offer enhanced control and process evaluation. Such control techniques have provided a means by which to minimize the impact of short circuit current clamping on the transfer process. They have also proven invaluable during the investigation of the current clamping boundary conditions when using the alternative control technique.

4.5.1 Extended Short Circuit and Arcing Period

During initial experimental welding trials to investigate the feasibility of short circuit current clamping in dip transfer GMAW extended short circuit transfer periods were sporadically observed. The existence of the extended short circuit transfer coincided with the implementation of the current clamp control. It was believed that certain short circuit process conditions would require a significantly higher electromagnetic pinch force to achieve the droplet transfer than was currently available when the short circuit current was clamped.

Following this investigation a control strategy was developed which allows the electromagnetic pinch force to be increased upon the detection of an extended short circuit transfer. Threshold detection logic was used to identify a short circuit time-out $T_{sc-lim}$ condition. The control strategy is based on a simple conditional test to determine whether the short circuit period has exceeded the time-out limit. If so the short circuit current clamp is released, which allows the current to incrementally rise until the molten bridge ruptures or upon achieving the current limit. Details of the control algorithm are shown in the flow diagram of Figure 4.4.
A similar control methodology has also been previously adopted by [53] to minimize the impact of stubbing in dip transfer GMAW. Based on this work and experimental investigations, short circuit time-out limits of 5ms for Ar-23%CO₂ and 6ms for CO₂ shielding gases were successfully implemented during welding trials. The transient voltage and current waveforms resulting from the implementation of the control strategy are illustrated in Figure 4.5.

Figure 4.4. Extended short circuit control algorithm

Figure 4.5. Short circuit time-out control

From the current waveform it can be seen that the detection of the short circuit time-out facilitates the release of the current clamp. The resultant increase in current and electromagnetic pinch force is then used to clear the short circuit. The implementation of this control strategy significantly enhanced the regularity of the short circuit period when using the alternative control technique.
Following on from this work, process conditions were sporadically observed when welding with CO₂ shielding which impacted significantly on the duration of the arcing period. The associated investigation and the strategy developed to minimize the impact of excess arcing periods on the weld process stability is discussed in detail in Section 5.9.

### 4.5.2 Short Circuit Process Monitoring and Spatter Identification

As discussed in Section 2.5 weld spatter in dip transfer GMAW is generated at the instance of the droplet to weld pool short circuit or at the re-establishment of the arc with the molten bridge rupture.

During experimental investigations of welding trials using CO₂ shielding an analysis of voltage and current waveforms revealed an abrupt premature interruption to the short circuit period and a subsequent re-establishment of an arc, this was believed to be caused by droplet repulsion. The analysis revealed that the droplet repulsion occurred generally within the initial 0.75ms of the short circuit period, which is supported by Bukarov & Ermakov [47] who reported similar observations from high-speed film of the dip transfer process using CO₂ shielding.

A monitoring strategy was developed and implemented for the purpose of identifying and differentiating the mechanisms of the observed weld spatter. Its primary function was to monitor and record the incidents of short circuit time-outs and droplet repulsion. The following flow diagram outlines the algorithm that was utilized for the short circuit process monitoring.
Threshold detection logic was utilized in both instances to identify short circuit time-out $T_{sc-lim}$ and droplet repulsion $T_{sc-repulse}$ conditions. The monitoring strategies were both based on conditional tests to: 1) determine whether the short circuit period had exceeded the time-out limit as discussed in Section 4.5.1. If so the time-out counter was incremented or 2) determine whether the short circuit period had not exceeded the repulsion time limit. If so the droplet repulsed counter was incremented. Short circuit time-out and droplet repulsion conditions will impact on the level of weld spatter generated. Both count variables can be considered indicative of the spatter levels that may be observed while short circuit current clamping is in use.

The detection of the extended short circuit period is based on the time-out limits discussed in Section 4.5.1 for Ar-23%CO$_2$ and CO$_2$ shielding gases. A droplet repulsion is registered if the short circuit period was prematurely interrupted within the initial 0.75ms of the transfer period.

4.5.3 Adaptive Control Approach for Ar-23%CO$_2$

The purpose of initial welding trials was to ascertain the feasibility of short circuit current clamping over a range of welding parameters and to identify conditions conducive for current clamping. The trials were performed using a shielding gas
mixture of Ar-23%CO₂. Adaptive control software was developed as a tool to automatically regulate the short circuit current clamp level, conditional on specific process criteria. The adaptive ‘self tuning’ control methodology exploited for this series of welding trials is outlined in the flowchart of Figure 4.7.

Figure 4.7. Current clamping adaptive control using Ar-23%CO₂ shielding

From the flowchart the detection of short circuit time-out event forms the basis of the control methodology’s conditional process criteria. Initially for each short circuit transfer when a time-out event is not detected the control systematically performs a conditional test on the clamp reduction flag, and if true permits a stepped decrement in the current clamp level. The sequence is continually repeated with each transfer until the eventual detection of a short circuit time-out. Upon the detection of a time-out event the control applies a step increment to the current clamp level and inhibits any further reduction through the disabling of the clamp reduction flag. The short circuit time-out counter, which registers the accumulated time-out events, is incremented.

For the subsequent short circuit transfer a conditional test is applied to the clamp reduction flag. If false a further conditional test is performed on the accumulated time-out count to verify if less than 4 detected time-out events have occurred and if the last
recorded time-out occurred more than 60 dip cycles (0.6-1.5s) earlier. If true the process is considered stable and the clamp reduction flag is re-enabled.

The above control logic is based on the assumption that periodically spurious process conditions can exist which may contribute to the premature disabling of the clamp reduction control. Therefore in all probability a stabilized welding process can be considered to exist if 60 consecutive transfer cycles have eventuated without the further detection of short circuit time-outs. The limitation on the control re-activation of the clamp reduction flag ensures a managed recovery from spurious process conditions with scope to explore the current clamping boundary before establishing an equilibrium between current clamping and imposed short circuit transfer limitations. Conversely the controlled current clamp increase in response to detected time-out events remains active during the welding process to ensure process recovery from over optimized clamping levels.

The principle focus of the adaptive ‘self tuning’ control was to establish the minimum level of short circuit current clamping that could be achieved without further incidences of short circuit time-out events. For diagnostic purposes the current clamp level is output to the operator screen in real time, along with other weld process data. A schematic example of the adaptive current clamp regulation is illustrated in Figure 4.8.

Figure 4.8. Adaptive control of the current clamp for Ar-23% CO₂

The example of the adaptive control demonstrates the step regulation being applied to the current clamp level (5A step intervals). The clamping level is decremented by 5A on the completion of the short circuit transfer with no time-out event detected and conversely incremented by 5A on the completion of a transfer outside the time-out limit.
4.5.4 Adaptive Control Approach for CO$_2$

The focus of the second set of welding trials was to assess the feasibility of using short circuit clamping for dip transfer GMAW with CO$_2$ shielding. Like the first set of welding trials these were directed at identifying the range of welding parameters and conditions by which short circuit current clamping could be practically implemented in the welding process.

Initially a similar control approach as that used for the Ar-23%CO$_2$ shielded trials was attempted. The control approach described in Section 4.5.3 proved unsuccessful when implemented due to the welding processes irregularity with CO$_2$ shielding which is caused by repelled droplet motion. During the initial phase of these trials short circuit time-out events were commonly detected, interspersed with lengthy periods of optimal short circuit droplet transfers periods. The investigation was therefore directed at developing an adaptive current clamp control methodology where the specified control criterion is minimally influenced by the observed irregular dip cycles. In place of the time-out control criteria adopted for Ar-23%CO$_2$ shielding, a control variable derived from the mean short circuit transfer time $T_{sc\text{-period}}$ was introduced using a moving average, with a one-second sampling interval. The sample period was chosen based on the sensitivity of $T_{sc\text{-mean}}$ to general process irregularities and variations. An example of the moving average utilized in this work is illustrated in Figure 4.9.

![Figure 4.9. Moving Average](image)

The principle focus of the 'self tuning' adaptive control technique used for this application was to establish the minimum level of short circuit current clamping while maintaining the mean short circuit transfer time $T_{sc\text{-mean}}$ within specified deadband limits. In the event the process variable $T_{sc\text{-mean}}$ drifts outside the upper or lower deadband limit for a preset period of time a control action is taken to regulate the
current clamp level, with the intention of restoring the control variable to its operating band. The specific control action taken is solely dependent on the deadband limit breached. The adaptive control methodology adopted for this series of welding trials is outlined in the following flow chart of Figure 4.10.

Figure 4.10. Current clamping adaptive control for CO₂ shielding

This form of adaptive control as can be seen in the flowchart is based on a deadband control philosophy with threshold detection logic utilized for the identification of excursions outside the deadband limits. The control strategy is based on a series of conditional tests which: 1) Determine whether the process variable $T_{sc-mean}$ has exceeded the upper limit. If true a further test is applied to determine whether the limit breach has existed for longer than 0.5s without a control action taken. If so the control increments the current clamp level or 2) determine whether $T_{sc-mean}$ is below the lower limit. If true a further test is applied to determine whether this limit breach has existed for longer than 0.5s without a control action taken. If so the control decrements the current clamp level.

In the event that the process variable $T_{sc-mean}$ remains within the deadband limits no control action is taken, with the existing current clamp level maintained. For diagnostic
purposes the current clamp level is output to the operator screen along with other weld
process data. The described control philosophy is illustrated in Figure 4.11.

![Figure 4.11. Adaptive control of the current clamp for CO₂](image)

The above example shown in Figure 4.11 is indicative of the implemented deadband
control with the self-tuning adaptive controller effectively regulating the process
variable $T_{\text{sc-mean}}$ within the control band limits by adaptively adjusting the current
clamp level. For this series of welding trials the lower and upper control band limits
were respectively set to 2.7 & 3.0ms.

Each of the adaptive and monitoring software systems described in Section 4.5 were
implemented to perform tasks within either the short circuit or arcing periods of the dip
transfer process. These tasks are generally embedded within the framework of the
process control software structure described in the following section.

4.6 Software Control
The configurable power source control system described in Chapter 3 was utilized as a
development tool for the alternative control technique. Central to the adaptable
environment provided by the control system is the customized control software, which
is downloaded to the DSP controller on system start-up. Its primary task is to ensure the
welding process is controlled within the specified operational parameters.

4.6.1 Software Description of the Current Control Waveform
For control purposes the dip transfer process was subdivided into specific process states.
The key-state transitions occur with each re-establishment of the short circuit and arcing
period. In contrast the sub-state transitions are detected at the completion of the wetting-
in and arcing current pulse periods. Details of these transition states and the
configurable waveform parameters utilized for the alternative control technique are shown in Figure 4.12.

![Figure 4.12. Alternative control waveform with primary parameters](image)

As can be seen a detailed range of configurable waveform parameters provide the control system with diverse control options. A description of these waveform parameters and their typical operating range is outlined in Table 4.1.

### Table 4.1. Alternate control parameter range

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Operating Range</th>
<th>Setpoint Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsc-wet</td>
<td>0.5-0.75ms</td>
<td>Short circuit - wetting-in period</td>
</tr>
<tr>
<td>Isc-rmp</td>
<td>100A/ms</td>
<td>Short circuit - current rate of change</td>
</tr>
<tr>
<td>Isc-clp</td>
<td>50-200A</td>
<td>Short circuit - current clamping level</td>
</tr>
<tr>
<td>Iarc-pk</td>
<td>200-325A</td>
<td>Arcing - peak pulse current</td>
</tr>
<tr>
<td>Tarc</td>
<td>0.5-4.5ms</td>
<td>Arcing - pulse period</td>
</tr>
<tr>
<td>Iarc-rmp</td>
<td>150 / 75A/ms</td>
<td>Arcing - current rate of change</td>
</tr>
<tr>
<td>Iarc-bkd</td>
<td>20-125A</td>
<td>Arcing - background current</td>
</tr>
</tbody>
</table>

Additional control parameters, which can be viewed from the operator interface shown in Figure 3.8, provide the ancillary parameters for the control system. These parameters are generally utilized within the control software to specify the conditions for key-state transition and operating boundaries of the welding process. A description of the ancillary control parameters and their typical operating range are outlined in Table 4.2.
Table 4.2. Alternate control parameter range

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Operating Range</th>
<th>Setpoint Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isc-max</td>
<td>400-500A</td>
<td>Maximum short circuit current. Software limit</td>
</tr>
<tr>
<td>Isc-min</td>
<td>20A</td>
<td>Minimum short circuit current</td>
</tr>
<tr>
<td>Iarc-min</td>
<td>15A</td>
<td>Minimum arcing current</td>
</tr>
<tr>
<td>Vsc-thres</td>
<td>5v</td>
<td>S/C detection. Rapid voltage fall below threshold</td>
</tr>
<tr>
<td>Varc-thres</td>
<td>12v</td>
<td>Arc detection. Rapid voltage rise above threshold</td>
</tr>
<tr>
<td>Tsc-limit</td>
<td>5-6ms</td>
<td>Excess short circuit duration. Time-out limit</td>
</tr>
<tr>
<td>Tarc-lim</td>
<td>20ms</td>
<td>Excess arcing period. Time-out limit</td>
</tr>
<tr>
<td>WFR-nom</td>
<td>1-10m/min</td>
<td>Nominal wire feed rate. Active when welding.</td>
</tr>
<tr>
<td>WFR-crp</td>
<td>1-2m/min</td>
<td>Creep wire feed rate. Active at starting.</td>
</tr>
</tbody>
</table>

An outline of the control software utilized for the development of the alternative control technique is presented in the following section. The control logic is based on four key or sub-state transitions, which are executed in a sequential order. The process control is dependent on the waveform and ancillary parameters pertaining to the executed state.

4.6.1.1 State 2 – Short Circuit Wetting-In Period

The key-state transition to state 2 is realized at the instance of short-circuiting between the droplet and weld pool. The event is characterized by an instantaneous decrease in welding voltage, to a level below that of the short circuit detection threshold \( V_{\text{weld}} < V_{\text{sc-thres}} \), that is defined by \( t_1 \). Upon the transition to this state the current is reduced from the arcing background level \( I_{\text{arc-bkd}} \) to a minimum short circuit level for the duration of the preset wetting-in period \( T_{\text{sc-wet}} \) (usually 0.5-0.75ms). The sub-state transition to state 3 is realized once the short circuit period exceeds the preset wetting-in time \( (T_{\text{sc-period}} > T_{\text{sc-wet}}) \), denoted by the event \( t_2 \).

4.6.1.2 State 3 – Short Circuit Control

Upon the control transition to state 3 the current increases at a rate predetermined by the short circuit ramp rate \( I_{\text{sc-rmp}} \). After this the current is clamped at a level dependent upon \( I_{\text{sc-clp}} \), where it is held until the molten bridge ruptures. In the event the molten bridge fails to rupture within a prescribed time period (usually 5-6ms) the short circuit
current clamp is released, which allows the current to incrementally rise until the molten bridge ruptures or upon achieving the software current limit.

The key-state transition to state 4 is realized once the molten bridge ruptures and the arc is re-established. This event is characterized by an instantaneous increase in welding voltage to a level above that of the arc detection threshold \( V_{\text{weld}} > V_{\text{arc-thres}} \), which is denoted by the event \( t_3 \).

### 4.6.1.3 State 4 – Arc Pulse Period

On the control transition to state 4 an arcing current pulse is applied with the intent of growing the droplet above a critical size and depressing the weld pool so as to minimize the likelihood of incipient short circuits. The magnitude and duration of the current pulse is dependent on the setpoints \( I_{\text{arc-pk}} \) and \( T_{\text{arc}} \). The sub-state transition to state 1 is realized once the arcing period exceeds the arcing pulse time \( T_{\text{arc-period}} > T_{\text{arc}} \), which is denoted by the event \( t_4 \).

### 4.6.1.4 State 1 – Background Arcing Current

Upon the control transition to state 1 the current is decreased at a rate determined by the dual slope setpoint \( I_{\text{arc-rmp}} \) to a background level defined by \( I_{\text{arc-bkd}} \). As stated earlier the key-state transition to state 2 is realized at the instance of short-circuiting between the droplet and weld pool where the instantaneous decrease in welding voltage is detected by the short circuit threshold, denoted by the event \( t_{5.1} \).

The dip transfer GMAW process with its regular short circuit and arcing events is well suited to the implementation of the state transition control described within this section. The greatest asset of the control methodology described is its ability to control the welding process without the need for pre-monitor detection of any event.

### 4.7 Alternative Control Experimental Results

#### 4.7.1 Experimental Setup

Welding trials were carried out in dip transfer GMAW using the alternative control technique and the experimental setup described in Chapter 3 utilizing the UOW research 400A inverter power source. Bead on plate (BOP) welds of 100mm length were
produced on 250×50×5mm mild steel plate using Ar-23%CO₂ and CO₂ shielding gases at a flow rate of 18 litres/min. The electrode was 0.9mm diameter mild steel which conformed to AWS5.18 ER70S-6 specification. The welding torch was stationary and fixed in a vertical position while the work-piece was secured to a movable bed. The Ar-23%CO₂ shielded welding trials were performed using contact tip to work-piece distances (CTWD) of 8, 16 & 20mm at a welding travel speed of 382 mm/min. The CO₂ shielded welding trials were performed using CTWD’s of 8, 12 & 16mm at a welding travel speed of 335 mm/min. A common wire feed rate of 5.32m/min was used for both sets of trials.

A selected combination of IArc-pk, IArc-bkd and Tarc welding parameters were chosen. The short circuit current clamp was optimized by the 'self-tuning' adaptive control methods described in Sections 4.5.3 & 4.5.4. The selected ranges of welding parameters used for the welding trials are detailed in Tables 4.3 & 4.4.

### Table 4.3. Welding parameter range using Ar-23%CO₂ shielding.

<table>
<thead>
<tr>
<th>CTWD mm</th>
<th>IArc-pk A</th>
<th>IArc-bkd A</th>
<th>Tarc ms</th>
<th>Tsc-wet ms</th>
<th>Isc-clp A</th>
<th>WFR m/min</th>
<th>T.Spd mm/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>200-300</td>
<td>40-110</td>
<td>1.5-2.0</td>
<td>0.5</td>
<td>Optimized</td>
<td>5.32</td>
<td>382</td>
</tr>
<tr>
<td>16</td>
<td>200-300</td>
<td>40-100</td>
<td>1.5-2.0</td>
<td>0.5</td>
<td>Optimized</td>
<td>5.32</td>
<td>382</td>
</tr>
<tr>
<td>20</td>
<td>200-300</td>
<td>40-100</td>
<td>1.5-2.0</td>
<td>0.5</td>
<td>Optimized</td>
<td>5.32</td>
<td>382</td>
</tr>
</tbody>
</table>

### Table 4.4. Welding parameter range using CO₂ shielding.

<table>
<thead>
<tr>
<th>CTWD mm</th>
<th>IArc-pk A</th>
<th>IArc-bkd A</th>
<th>Tarc ms</th>
<th>Tsc-wet ms</th>
<th>Isc-clp A</th>
<th>WFR m/min</th>
<th>T.Spd mm/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>225-325</td>
<td>20-80</td>
<td>1.5-2.5</td>
<td>0.75</td>
<td>Optimized</td>
<td>5.32</td>
<td>335</td>
</tr>
<tr>
<td>12</td>
<td>200-300</td>
<td>20-80</td>
<td>1.5-2.0</td>
<td>0.75</td>
<td>Optimized</td>
<td>5.32</td>
<td>335</td>
</tr>
<tr>
<td>16</td>
<td>225-275</td>
<td>20-80</td>
<td>1.25-1.75</td>
<td>0.75</td>
<td>Optimized</td>
<td>5.32</td>
<td>335</td>
</tr>
</tbody>
</table>

At approximately the midpoint of each weld the oscilloscope and data acquisition system was triggered, recording a 1 second interval of the welding voltage and current. The acquired data was later used to correlate welding process information relating to stability index, short circuit resistance, heat input, mean voltage and current.
After welding, cross sections of the welds were taken, polished, etched and photographed to determine the weld geometry, which was later correlated against calculated heat input and current.

In addition a duplicate system (as described in Chapter 3) was built for Thermadyne in the USA who carried out manual welding trials using the alternative control technique. The feedback resulting from these additional welding trials is discussed later in this Chapter.

4.7.2 Droplet Transfer Modeling

4.7.2.1 Transfer Time to Droplet Volume

A study of the bridging transfer was performed using a simulation model described in Section 4.4.1 under a Matlab environment. The study focused on the impact current clamping, droplet size and current rate of change has on the bridging transfer. The model was executed using a surface tension $\gamma$ of 0.9 N/m [22], a molten metal density $\rho$ of $7.87 \times 10^3$ kg/m$^3$ [92] and an electrode wire diameter of 0.9mm.

The model control methodology was based on the detailed alternative control waveform of Figure 4.12. Initially the current is held to 40A during a wetting-in period of 0.75ms. On the completion of the wetting-in period the current rises at a rate specified by the short circuit current ramp $I_{\text{sc-rmp}}$ until clamped, where it is held for the remainder of the transfer period. The simulation is then terminated once the diameter of the molten bridge is less than 0.01mm at which point the molten bridge is assumed to have ruptured. This assumption is based on an analysis by Zaruba [51] into the electrical explosive force during the bridge rupture.

The analysis by Zaruba revealed that an electrical explosion of a molten bridge with a constant current flow of 390A should take place once the bridge diameter reaches 0.06mm. As the short circuit current range for this analysis is much lower than 390A, then the approach adopted by Zaruba would suggest that an electrical explosion of the molten bridge should occur once the bridge diameter reaches 0.01-0.04mm for a corresponding current range of 15-200A. As the short circuit energy generated by the alternative current waveform is limited by both a wetting-in and current clamping phase
the value of the generated short circuit energy is predictably at the lower end of this constant current range. Therefore a bridge diameter of 0.01-0.02mm at rupture is considered appropriate for the model. An example of the simulated current control waveform is illustrated in Figure 4.13.

![Figure 4.13. Simulated current control waveform](image)

Initial modelling of the transfer process was directed towards evaluating the transfer time with respect to current clamp levels of 0, 100 & 200A for a droplet volume ranging from 0.6-1.6mm³. The short circuit current ramp (I_{sc-rmp}) was fixed at 100A/ms. The results of this modelling which illustrates the relationship between the transfer time and the droplet volume for fixed levels of current clamping is shown in Figure 4.14.

![Figure 4.14. Transfer time vs Droplet Volume (Simulation)](image)

The simulation results suggest a correlation between the transfer time and droplet volume, which is linear at constant levels of current clamping. From these results it can be concluded that the transfer time would be expected to increase as the current clamping level is reduced or the droplet volume is increased. This observation is well supported by other authors [5, 7].
4.7.2.2 Current Rate of Change

Modelling of the transfer process was expanded to evaluate the impact the rate of change in short circuit current has on the duration of the transfer period. Simulations of the model were carried out for a current ramp rate of 75, 100 & 200A/ms. The level of current clamping and droplet volume were maintained constant at 150A and 0.94mm³ respectively (in reality the droplet volume may vary by 10%). The impact the current rate of change has on the duration of the transfer period is illustrated in Figures 4.15(a), (b) & (c) which are representative of the entire short circuit period.

![Figure 4.15. Short circuit current rate rise](image)

(a) Current rate rise 75A/ms  
(b) Current rate rise 100A/ms.  
(c) Current rate rise 200A/ms.

An analysis of the simulated current waveform suggests the duration of the droplet transfer period would decrease in response to increasing the current ramp rate. From the above results the droplet transfer time can be seen to decrease from 2.55ms for a current rate rise of 75A/ms to 2.45ms when the rate rise is increased to 200A/ms. This observed decrease in the transfer time as the current rate rise is increased can be attributed to the increased influence of the electromagnetic pinch force when the short circuit current attains the current clamp level earlier in the transfer period.
4.7.2.3 Optimization of the Current Clamp

Current clamping as a control technique can have a significant impact on the level of spatter generated during the welding process. Its implementation is expected to impact to some degree on the transfer time but under particular welding conditions may adversely impact on the regularity of the transfer process if excessively low levels of current clamping are applied. Even though low clamping levels may be utilized to promote spatter reduction, the likelihood of undesirable lengthy transfer periods in the event of process anomalies is increased. Alternatively high clamping levels will ensure a greater consistency in the droplet transfer period, but may not reduce weld spatter during the bridge rupture to within desired levels. In practice process conditions can vary to the extent where some droplet transfers may be realized prior to the short circuit current being clamped. Under such circumstances reductions in weld spatter are still achieved by virtue of the lower level of current that exists during the bridge rupture.

Based on the scenarios just described, a strategic approach for the selection of optimum current clamping may be to identify a level of current above which the generated spatter is unacceptable. Using this approach the current clamp can be utilized to perform the task of limiting the maximum level of weld spatter, with relatively short droplet transfer periods still realized prior to clamping. This approach can achieve optimum spatter reduction and process stability. To demonstrate this clamping strategy a simulation was performed using a current clamp of 200A, a current ramp rate of 100A/ms, while the droplet volume was increased from 0.70mm$^3$ to 1.0mm$^3$. The current waveforms based on the simulated results are shown in Figures 4.16 (a) & (b).

![Current control waveform](image)

(a) Larger Droplet Volume  
(b) Smaller Droplet Volume

Figure 4.16. Current control waveform (Simulation)
For the specified current control waveforms the larger volume droplet is seen to transfer in 2.6ms with current clamping applied during the later stages of the transfer period as shown in Figure 4.16(a). By comparison as illustrated in Figure 4.16(b) the smaller volume droplet transfers within 2.1ms with the transfer realized prior to achieving current clamping.

The above results would tend to suggest that optimal spatter reduction and process stability can be achieved over a wide range of welding conditions if the function of the current clamp is directed at maintaining the short circuit current and generated weld spatter to within accepted limits.

4.7.3 Validation of the Transfer Model
4.7.3.1 Transfer Time to Droplet Volume
To assess the validity of the model with respect to an actual welding environment process data was extracted from transient voltage and current waveforms of Ar-23%CO₂ and CO₂ shielded welds carried out over a range of wire feed rates and travel speeds. For this evaluation process data pertaining to the short circuit transfer time and dip frequency were of particular interest. The data providing the basis for an empirically derived relationship that correlated the transfer time as a function of the estimated droplet volume for the actual welding environment. The estimated droplet volume was derived as a function of the dip frequency and wire feed rate. For this series of welding trials a current clamping level of 150A for Ar-23%CO₂ shielding and 200A for CO₂ shielding was maintained for the duration of the trials. This noted distinction in the current clamping levels for the differing shielding gases is discussed later in this Chapter. The empirically derived relationship of the transfer time as a function of the droplet volume for both Ar-23%CO₂ and CO₂ shielded welds is shown in Figure 4.17.
As can be seen from the above graph the correlation between the transfer time and droplet volume of either Ar-23%CO₂ or CO₂ shielding for droplet volumes less than 1mm³ are relatively similar with the transfer time of the Ar-23%CO₂ shielded droplet slightly higher than that of the CO₂ shielded droplet. This is expected, considering the lower current clamp level used for the Ar-23%CO₂ shielded welds. Further droplet growth above 1mm³ for the CO₂ shielded droplet sees a continued linear increase in the relationship between the transfer time to droplet volume.

An assessment of the theoretically and actual derived correlation between the transfer time and the droplet volume was performed to determine the accuracy of the short circuit transfer model and its potential as a tool for developing current clamping strategies. Modeling of the short circuit transfer was performed using a current clamp of 175A and a current ramp rate of 100A/ms. The selection of the current clamp level is based on an analysis of actual CO₂ shielded weld data which revealed the completion of numerous droplet transfers prior to the current reaching the 200A clamping level. As numerous Ar-23%CO₂ and CO₂ shielded droplets were transferred with the short circuit current between 150-175A the chosen value was considered appropriate. For comparison purposes the simulated and actual relationships between the transfer time and the droplet volume are overlaid and displayed in Figure 4.18.
From the information contained in Figure 4.18 the accuracy of the model was assessed against the experimentally derived curves. The transfer characteristic of the model was chosen as the principle curve. The CO$_2$ shielded transfer characteristic for a droplet volume of 0.6-1.4mm$^3$ was estimated to have a standard deviation from the principle curve of 0.1348ms. By comparison the standard deviation of the Ar-23%CO$_2$ shielded transfer characteristic for a droplet volume of 0.6-1.1mm$^3$ is 0.2111ms. As the primary function of the model is the development of current clamping strategies the reported level of standard deviation is acceptable considering the model's assumptions.

The discrepancies that exist between the simulation and actual transfer characteristic curves can be attributed to the simplification and assumptions made when defining the analytical model: 1) The contact region interface between the bridge and weld pool will vary in area during the transfer process; however to simplify the model it is assumed to be constant. 2) The weld pool movement, which significantly influences the droplet transfer during the welding process, is considered flat and stable. 3) Even though it is assumed in the model that all size droplets will naturally transfer, in practice small droplets tend to form a stable meniscus and will not transfer under the sole influence of surface tension. No allowance has been made in the model for this phenomenon.

4.7.3.2 Current Clamping

The realization of short circuit droplets transferring prior to current clamping has not only been identified through the modeling of the droplet transfer but also during actual CO$_2$ shielded welding trials. An analysis of transient voltage and current waveforms of the dip transfer GMAW process has revealed instances where arcing and short circuit transfer periods can significantly differ between consecutive dip cycles. This is
demonstrated in Figure 4.19 where the portion of the arcing period (0.1-0.105s) that precedes the short circuit would suggest the duration of that arcing period was sufficient to achieve reasonable droplet growth. This is confirmed by the first short circuit transfer, which was completed in approximately 4ms (0.106-0.11s) with the short circuit current clamped for 2ms (0.109-0.11s) prior to the molten bridge rupture.

By contrast the following arcing period is approximately 6ms (0.11-0.116s) and notably shorter than the previous arcing period. As a consequence less droplet growth is expected. The impact of the shorter arcing period can be seen in the corresponding short circuit period where the droplet transfer is completed within 2.2ms (0.1163-0.1185s), prior to current clamping. As would be expected, the droplet growth achieved in the preceding arcing period significantly influences the short circuit transfer time.

As can be appreciated by the above discussion the degree to which surface tension and the electromagnetic pinch influences the transfer process can vary significantly, and must be considered when devising any form of spatter reduction strategy. For this example Figure 4.19 clearly demonstrates how optimum weld spatter reduction and process stability can be achieved through the implementation of the short circuit current clamp as a maximum current limiter as proposed earlier in this section. The experimentally observed process conditions confirm the validity of the transfer model and the results of Section 4.7.2.3 and further underscore the model's suitability for developing current clamping methodologies.

4.7.4 Verification of Short Circuit Period Limits
The modeling of the transfer process has shown that the use of short circuit current clamping can significantly impact on the transfer period duration due to the reduced
electromagnetic pinch influence. A detailed analysis of the bridging transfer by Choi and Yoo [7] suggests that short circuit current clamping may extend the droplet transfer period by 0.5-1.5ms.

As a comparative basis for this work, welding trials were carried out to identify typical short circuit current and transfer periods that exist without the presence of any current limiting methodology. This was achieved through disabling the current clamp control of the alternative control technique. Welding trials were performed using Ar-23%CO₂ shielding, a wire feed rate of 5.8 m/min and welding parameters as shown in Figure 4.20. As illustrated by the transient current waveform the short circuit current was initially held low during the wetting-in period to conform to the approach taken by the alternative and other current control techniques. On completion of the wetting-in period the current was then increased at a ramp rate of 100A/ms until the molten bridge ruptured. This chosen rate of rise was derived experimentally from typical constant voltage control welding data, and based on reported work by Paton and Zaruba [93] should be minimized to a level that is easily tolerated by the process. The resultant transient voltage and current waveform is displayed in Figure 4.20.

![Figure 4.20. Unclamped current control waveform](image)

From this example the current rate rise on the completion of the wetting-in period is clearly seen, with a short circuit current of 300A attained prior to the molten bridge rupture. In practice for this experimental setup the maximum level of current was observed to vary between 250-350A with corresponding transfer periods of 2.75-3.75ms. A simple analogy can be drawn between this current control waveform and the constant voltage control technique discussed in Chapter 2. In both cases no form of control is available to limit or reduce the current during the short circuit period, while the current rate of rise has a significant impact on the welding process and the generated
spatter. The significant difference being the increased influence of surface tension through the introduction of a wetting-in period.

Based on the above results for the Ar-23%CO₂ shielded welds a maximum short circuit transfer period of 5ms was selected as the threshold for detecting extended short circuit transfer periods. An explanation of the detection and its uses is provided elsewhere in this Chapter. After completing preliminary investigations the focus of the work was then directed at determining practical boundaries for short circuit current clamping whilst still maintaining acceptable levels of process stability. The result of this work is described in the following sections of this Chapter.

4.7.5 Alternative Control – Adaptive 'Self Tuning' Methodology

The basic premise of the alternative control technique as discussed earlier in this Chapter is “that providing a critical sized droplet is developed prior to short-circuiting, surface tension can be utilized as the predominant droplet detachment force rather than electromagnetic pinch”. Based on this premise initial research was directed towards investigating the practical range that short circuit current clamping could be used in dip transfer GMAW applications.

This first set of welding trials involved the implementation of the alternative control technique in conjunction with the adaptive ‘self tuning’ control methodology discussed in Section 4.5.3 for Ar-23%CO₂ shielded welds. For each weld run the transient voltage and current waveforms were captured. This data provided statistical and process information, a graphical representation of welding process events and the attained current clamp levels. The clamping level at the operator interface was recorded upon the completion of the weld. Typical examples of clamping levels achieved while using the adaptive ‘self tuning’ control methodology with Ar-23%CO₂ shielding are illustrated by the transient waveforms of Figures 4.21(a) & (b).
An analysis of the welding data has revealed that minimum current clamping levels of 10-25A were on occasion achieved when welding parameter selections facilitated large droplet growth, which was easily recognized from the relatively low dip frequencies. However it was noted that once a minimum level of current clamping was achieved, further droplet growth tended to produce a higher regularity of transfer periods outside the adaptive control limits. This was most likely caused by the additional time required to transfer the larger volume droplet but in some incidences may have been the result of irregular droplet motion as a consequence of the additional growth.

The second set of welding trials involved the implementation of the alternative control technique in conjunction with adaptive ‘self tuning’ control methodology discussed in Section 4.5.4 for CO2 shielded welds. As with the welding trials carried out using Ar-23%CO2 shielding transient voltage and current waveforms were captured during the welding process with the current clamp level recorded on the completion of the weld. Typical examples of clamping levels achieved using the adaptive ‘self tuning’ control methodology for CO2 shielding are illustrated by the transient waveforms in Figures 4.22(a) & (b).
An analysis of the welding data revealed that minimum current clamping levels of 145-150A were on occasion achieved for particular selected welding parameters. This higher level of current clamping when compared to that achieved using Ar-23%CO₂ can be attributed to the higher process irregularity that is encountered when using CO₂ shielding, along with the stringent control deadband of 2.7-3.0ms that was utilized to ensure the short circuit transfer period remained within the operating boundaries of commercially available dip transfer systems.

By comparison the greater process regularity that was witnessed when using Ar-23%CO₂ shielding allowed the adaptive control to be afforded a wider scope to explore the operational limits. From these trials a mean transfer period of 2.7-4.2ms was observed for current clamping levels between 10-80A.

The minimum and optimum clamping levels identified from the welding trials are shown in Table 4.5. The concept of optimum clamping is discussed earlier in Section 4.7.2.3 with the selection of such values discussed in the following sections of this Chapter.

<table>
<thead>
<tr>
<th>Shielding Gas</th>
<th>Minimum Clamp Level</th>
<th>Optimum Clamp Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar-23%CO₂</td>
<td>10</td>
<td>150</td>
</tr>
<tr>
<td>CO₂</td>
<td>145</td>
<td>200</td>
</tr>
</tbody>
</table>
4.7.6 Weld Spatter

4.7.6.1 Spatter Graduation

To analyse the impact short circuit current clamping has on the weld spatter generated during the bridge rupture a visual evaluation approach was devised, based on a graduated spatter index that assesses quantity and projected length. The following diagram demonstrates the spatter graduation approach devised for this work.

![Figure 4.23. Spatter graduation levels](image)

The diagram illustrates primary graduation levels, which are categorized as short (S), medium (M) and long (L) projected spatter, with intermediate graduations providing a higher degree of differentiation. A description of the primary and intermediate graduation levels is provided in Table 4.6 where the index increases in accordance with the level of spatter.

<table>
<thead>
<tr>
<th>Spatter Index</th>
<th>Index Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>Ultra fine - short projected spatter</td>
</tr>
<tr>
<td>2.5</td>
<td>Very fine - short projected spatter</td>
</tr>
<tr>
<td>3.75</td>
<td>Fine - short projected spatter</td>
</tr>
<tr>
<td>5</td>
<td>Fine to coarse - short to medium projected spatter</td>
</tr>
<tr>
<td>5.62</td>
<td>Fine to coarse - short to medium projected spatter</td>
</tr>
<tr>
<td>6.25</td>
<td>Coarse - medium projected spatter</td>
</tr>
<tr>
<td>7.5</td>
<td>Coarse - medium to long projected spatter</td>
</tr>
<tr>
<td>8.75</td>
<td>Coarse - medium to long projected spatter</td>
</tr>
<tr>
<td>10</td>
<td>Very coarse - long projected spatter</td>
</tr>
</tbody>
</table>

Based on this index welds generating short projected fine spatter were assessed as having an index of 5 or below with longer projected coarse spatter assessed above this level. Examples of the graduated index are provided by the following images of the welding process using Ar-23%CO₂ shielding.
4.7.6.2 Approach to Spatter Graduation

The generated spatter during the bridge rupture for the above welding conditions was assessed using this visualization approach. However in practice this approach can be compromised if the generated weld spatter is seen to comprise a portion attributable to excessive short circuit time-outs and or droplet repulsion (ball spatter). In such circumstances a collaboration of approaches may be required.

Figure 4.24. Examples of graduated spatter

The adaptive ‘self tuning’ control technique adopted for the Ar-23%CO₂ shielded welding trials was intended by its methodology to principally lower the current clamp level until short circuit time-outs were detected. As a consequence of this approach it is reasonable to assume that the current flow during the molten bridge rupture was that specified by the level of current clamping and therefore considered indicative of the generated weld spatter. As the occurrence of ball spatter was not readily observed during this series of welding trials a visualization approach for the graduation of weld spatter was considered appropriate and proved to be quite effective.
In contrast when welding with CO₂ shielding as discussed earlier in this Chapter an increased likelihood of process irregularity and droplet repulsion exists. As such it was found necessary when assessing the weld spatter to utilize a collaboration of the visualization approach in conjunction with recorded incidents of short circuit time-out and droplet repulsion. During these welding trials instances of two concurrent levels of spatter could occasionally be observed. One comprised usually a fine level of spatter, which was assumed to be generated during the bridge rupture. The second, a coarser ball spatter, resulting from droplet repulsion at the instance of short-circuiting. As the function of this assessment was to evaluate the impact short circuit clamping had on spatter generation during the molten bridge rupture a visualization of both levels of spatter was performed. This was compared against the recorded short circuit clamp level and the incident of short circuit time-out and droplet repulsion. If a high incidence of droplet repulsions was recorded, coupled with a current clamp less than 200A and a low incidence of short circuit time-outs; it was assumed that the generated fine spatter was a consequence of the bridge rupture and was accordingly graded between 3.75-5.0, while the recorded incident of droplet repulsion verified the source of the coarser ball spatter.

To visually assess the impact short circuit current clamping has on weld spatter during the bridge rupture, the resultant graduations for both Ar-23%CO₂ and CO₂ shielded welding trials were plotted as a function of the current clamp level. The following relationships are shown in Figures 4.25(a) & (b).

![Figure 4.25. Weld spatter index as function of current clamp level](image)

(a) Ar-23%CO₂ shielding  
(b) CO₂ shielding

As can be seen from Figure 4.25(a), which represents the relationship between the graduated spatter and the current clamp level for Ar-23%CO₂ shielding, very fine to fine spatter is generated when the short circuit current is clamped below 80A, with
minimal spatter generated when the short circuit current was clamped to 150A and below.

By comparison Figure 4.25(b) which represents a similar relationship for CO₂ shielding, suggests higher levels of spatter are generated when welding with CO₂ compared to Ar-23%CO₂ shielding, with minimal spatter generated when the short circuit current is clamped to 200A and below.

From these results it can be concluded that reductions in weld spatter are achieved when utilizing a short circuit current clamping methodology. In particular this is so when the current clamp level is maintained at or below 150A for Ar-23%CO₂ shielding and 200A for CO₂ shielding with the existing experimental setup. These result although encouraging must also be evaluated with respect to the weld process stability index to ascertain whether the welding process remains stable for the noted ‘optimum parameters’.

### 4.7.7 Stability Index

Descriptive statistical methods are used widely to evaluate the regularity and consistency of the welding process. The extracted data is often used to generate a measure of the weld stability referred to as the stability index. This index value when applied to a short-circuiting transfer process is usually derived from parameters relating to the voltage, current or short circuit and arcing periods. The measure having been used by other researchers [94, 95, 96, 97, 98, 99] in the study of dip transfer GMAW. For the current welding trials using Ar-23%CO₂ and CO₂ shielding gases one-second sample periods of the transient welding voltage and current waveforms were captured using the data acquisition systems described in Chapter 3. For this work statistical data of the dip cycle was extracted and used to calculate the weld process stability index, which was defined by the following equation.

\[
\text{SI} = \left(1 - \frac{\sigma_c}{\mu_c}\right) \quad (4.6)
\]

where SI is defined as the weld process stability index which ranges from 0-1, with \(\sigma_c\) the standard deviation and \(\mu_c\) the mean of the dip cycle time. Using this equation the stability index can be expected to increase as the regularity of the welding process
improves. From general experience when using the alternative current control waveform described earlier in this Chapter, it has been noted that a stability index above 0.65 corresponds to a good weld.

To evaluate the extent short circuit current clamping impacts on the stability of the welding process the stability index was correlated and plotted as a function of the current clamp level. The resultant data from the welding trials using Ar-23%CO₂ and CO₂ shielding is shown in Figures 4.26(a) & (b).

As can be seen from Figure 4.26(a), which represents the relationship between the stability index and the current clamp level for Ar-23%CO₂ shielded welds, the mean stability index decreases slightly from 0.76 with the current clamp above 300A to 0.72 when the current clamp is below 30A. By comparison Figure 4.26(b), which represents a similar relationship for CO₂ shielded welds the mean stability index remains relatively constant at 0.725 for the range of current clamping investigated.

To assess the impact of short circuit current clamping on the weld process stability the data contained in Figures 4.26(a) & (b) was evaluated with respect to the optimum current clamp levels reported in Section 4.7.6.2. A short circuit current boundary of 150A for Ar-23%CO₂ and 200A for CO₂ shielding were inserted into Figures 4.26(a) & (b) respectively along with a stability index boundary of 0.65.

An analysis of the operating region for either shielding gas suggests the majority of welds were performed under stable welding conditions. Those identified as having a stability index less than 0.65 were generally the product of attempts to expand the
alternative control technique's operating envelope. From the above results it can be concluded that the alternative control technique can function within an acceptable operating region whilst not adversely impacting on the weld process stability.

4.7.8 Verification against Common Control Techniques

Improvements to any control or welding process can only be truly assessed when evaluated against industry accepted control methodologies and power sources. For the purpose of this evaluation the alternative control technique was assessed against the conventional voltage control technique and also a current control technique, whose control waveform is derived from a sophisticated inverter power source specifically developed for dip transfer GMAW.

The conventional constant voltage control as illustrated in Figure 2.8 was implemented through a commercially available multi-function inverter welding power source, which was selected for GMAW operation. The current control technique as illustrated in Figure 2.14 was generated using a Lincoln STT TM power source which utilizes pre-monition detection of the molten bridge rupture for the purpose of reducing weld spatter.

The control techniques were each evaluated under similar dip transfer GMAW conditions using a CO₂ shielding gas. The welding torch was fixed in a vertical position to the work-piece with a $CTWD$ of 8mm. Bead on plate (BOP) welds of 100mm length were produced on $250\times50\times5\text{mm}$ mild steel plate with CO₂ shielding at 18 litres/min. The electrode was 0.9mm mild steel wire conforming to ER70S-6 AWS specification.

For comparative purposes the parameter setup of the respective welding power sources provided similar levels of mean welding current $I_{\text{mean}}$. Initially trials incorporating the alternative control technique utilized the parameters specified in Table 4.7 with a wire feed rate of 5.32 m/min. This setup produced a resultant mean welding current of 99A with the generated spatter considered comparable with that produced using the Lincoln STT with a resultant mean current of 85A. A further comparison of the alternative control technique was performed with the WFR reduced to 5 m/min and the resultant
mean welding current now 91.6A. The process variables used in the assessment of the control techniques are displayed in Table 4.7.

Table 4.7. Welding process variables.

<table>
<thead>
<tr>
<th>Control Technique</th>
<th>Power Source Setup</th>
<th>WFR</th>
<th>Tr.Spd</th>
<th>Photo Fig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional CV Control</td>
<td>$I_{\text{mean}}$ - 100 A</td>
<td>5.32</td>
<td>335</td>
<td>4.27(a)</td>
</tr>
</tbody>
</table>
| Lincoln STT Current Control | $I_{\text{mean}}$ -85 A  
$I_p$ -275A, $I_{\text{bkd}}$ -75A | 5.32| 335    | 4.27(b)    |
| Alternate Current Control | $I_{\text{mean}}$ -91.6A, $I_{\text{sc-clp}}$ -200A  
$I_{\text{arc-pk}}$ -300A, $I_{\text{arc-bkd}}$ -60A,$T_{\text{arc}}$ -2.2ms | 5   | 335    | 4.27(c)    |

The following images taken of the dip transfer GMAW process using CO₂ shielding provide a visual comparison of the spatter generated when using either of the three control techniques with a fixed $CTWD$ and controlled welding travel speed.

(a) Conventional CV Control          (b) Lincoln STT power source

(c) Alternate control technique

Figure 4.27. Visual comparison of dip transfer control techniques

A subjective visual comparison of the control techniques suggests the alternative current control using short circuit current clamping under this experimental setup generated a level of spatter which was considered comparable to that produced when welding with
the Lincoln STT power source. This level of spatter was significantly lower than that generated when welding with the conventional constant voltage control technique.

4.8 Manual Welding Trials

Welding trials of the alternative control technique were performed by Thermadyne in the USA to review the performance of the control technique in a manual welding environment. Prior to this all welding involving the described control technique had been performed using the experimental test equipment described in Chapter 3 with varied but controlled levels of $CTWD$ and welding travel speed. A range of experimentally derived welding parameters were issued to Thermadyne for the trials based on a $CTWD$ of 12mm for either Ar-23%CO$_2$ or CO$_2$ shielding and 0.9mm diameter ER70S-6 mild steel copper coated for a wire feed rate of 5-6 m/min on 5mm mild steel plate.

The manual welding trials were significant in that they provided the first instance of independent assessment of the alternative control technique in an environment prone to variation in $CTWD$ and weld travel speed. The importance of these trials in regards to this research was not initially in the welds achieved but the identification of potential process impediments to weld stability.

Initially the manual welding trials clearly identified two process impediments that impacted significantly on the weld stability while using CO$_2$ shielding. The first related to the occasional incidence of an unusually large droplet being grown and repulsed as ball spatter. An initial investigation of transient voltage and current waveforms of the welding process identified the odd occurrence of an abnormally long arcing period, which it was suspected contributed to the growth of the unusually large droplet. This reported phenomenon however is not just confined to this particular control approach but has also been observed when using other control techniques with CO$_2$ shielding. It was hypothesised that the constricted localized arc root, commonly associated with a CO$_2$ shielding gas, was creating an upward directed deflection of the droplet, which on occasion inhibited the ensuing short circuit, resulting in an abnormal extended arcing period and droplet growth. The hypothesis, investigation and the implemented control strategy to compensate for this phenomenon are discussed in Chapter 5.
The second reported process impediment related to an occurrence of a “long short circuit period, which the control had difficulty clearing”. An investigation of the problem revealed an incident where premature arc voltage detection caused the key-state transition to arcing control prior to having cleared the short circuit. This incident though not regularly witnessed would only occur during an extended short circuit period after the release of the current clamp. The increase in short circuit current directly contributes to an increase in the short circuit voltage drop, which on occasion exceeded the arc voltage threshold. The investigation and the adaptive threshold control that was implemented to address this issue are discussed in some detail in Chapter 5.

Upon addressing these reported process irregularities further manual welding trials were performed. Most of the welds performed by Thermadyne were fillet welds on 3mm mild steel plate, with the welder tending to gravitate to a CTWD of approximately 15mm. The manual CO₂ shielded trials were reported to produce some very clean welds, with very low spatter levels and reasonable weld stability. An extension of these trials was directed towards welding down a gap, producing a flat bead profile, followed by a good reverse bead with minimal spatter. Similar results were also reported for the Ar-23%CO₂ shielded trials, which by comparison produced a finer bead ripple and a cleaner looking weld.

4.9 Summary

An alternative control approach has been developed in the present work for dip transfer GMAW. It is based on the premise that providing a critical sized droplet is developed prior to short-circuiting then surface tension can be utilized as the predominant droplet detachment force rather than electromagnetic pinch. Fundamental to this control approach is a short circuit current clamping methodology, which clamps the maximum short circuit current to levels lower than normally encountered using conventional constant voltage control techniques. This effectively diminishes the electromagnetic pinch influence while enhancing surface tension as a predominate transfer mechanism.

The alternative control methodology like other dip transfer control techniques discussed in Chapter 2 endeavours to de-couple the control of short circuit and arcing period. The current clamp methodology is fundamental to the control of the short circuit transfer, while the selection of the arcing parameters is pivotal to the control of heat input and the
optimization of the welding process. Unlike the control methodologies proposed by other authors [74, 79] which place strong dependence on premonition detection of the ensuing molten bridge rupture and require a power source with substantially instantaneous current response capabilities under short-circuiting conditions. The alternative control approach requires no premonition detection and can be implemented in conjunction with conventional inverter power sources.

The dip transfer GMAW process with its regularity of short circuit and arcing events is well suited to the implementation of a state transition control methodology, which for this work required the welding process to be subdivided into four specific process states. The key-state transitions occur with each re-establishment of the short circuit and arcing period, and the sub-state transitions upon detecting the completion of the wetting-in and arcing current pulse period. For this application the task of the respective states was primarily to control the short circuit wetting-in, the current clamping, the droplet formation and the arc heating. The execution of each state is conditional on the detection of the appropriate transition event, and the process control dependent on the waveform and ancillary parameters pertaining to that state.

An analytical model of the short circuit transfer period was developed to simulate the impact short circuit current clamping and droplet volume has on the transfer process. The results attained through the model suggest the transfer period should increase as the level of current clamping is reduced, the droplet volume is increased or the current ramp rate decreased which will impact on the electromagnetic pinch influence. An evaluation of the short circuit transfer model using the emulated alternative current control waveform was performed with respect to empirically derived transfer characteristics. The resulting evaluation verified the appropriateness of the transfer model as a tool for developing current clamping methodologies.

In particular the transfer model has been invaluable for understanding the welding process when subjected to significant variations in transfer conditions and the impact this has on the current clamped droplet transfer. These variable transfer conditions which were regularly witnessed during the CO₂ shielded welding trials, resulted in some droplets being transferred prior to the clamping of the short circuit current while others required current clamping until the molten bridge ruptured. The use of the transfer
model in demonstrating this condition has proven advantageous to the devising of a strategy aimed at identifying optimum current clamp levels for actual welding applications. The proposed strategy is required to fulfil two criteria. The first is that maximum weld spatter is limited to an accepted level, and the second that the weld process stability is maintained over a wide range of welding conditions, thereby providing the operator with a low spatter stable weld.

Adaptive 'self tuning' control methodologies were developed to assess the feasibility of short circuit current clamping as a control mechanism for dip transfer GMAW. These were developed specifically for welding applications using argon based or CO₂ shielding gases where they have been designed to automatically regulate the short circuit current clamp level, conditional on a specific process criteria. For welding trials using Ar-23%CO₂ shielding the adaptive control methodology is based on a threshold controller, which assesses the duration of the transfer period with respect to the short circuit time-out threshold. By comparison for welding trials using CO₂ shielding the adaptive control methodology is based on a deadband controller which utilizes a control variable derived from the mean transfer period. Using the selected control criteria for each of the shielding gases, minimum current clamping levels of 10-25A for Ar-23%CO₂ shielded and 145-150A for CO₂ shielded welds were achieved by means of the adaptive ‘self tuning’ control methodologies.

During the evaluation and assessment of short circuit current clamping as a metal transfer control mechanism various process irregularities were identified. In circumstances where the process irregularity was noted during the short circuit period it was generally established that the irregularity was a direct consequence of the implemented current clamping methodology, while process irregularities identified during the arcing period were usually attributed to the welding process. As a consequence of these findings ancillary control strategies were devised and implemented to addresses these issues and enhance the weld process stability when utilizing the alternative control technique.

The principal focus of this work has been to develop a strategy that provides process enhancements and spatter reduction to the dip transfer GMAW process. As such it was necessary to formulate a method by which to reliably assess the impact short circuit
current clamping has on the generated weld spatter during the bridge rupture. To achieve this a graduated spatter index was devised, based on a visual approach that assesses the quantity and projected length of the spatter. This approach when utilized for welding applications where the molten bridge rupture is the primary source of the generated spatter will provide a consistent and reliable means of assessment. However this approach can be compromised if the components of weld spatter comprise more than one source. Under such circumstances a combination of approaches can be utilized which not only evaluate the weld spatter but also identify the source.

An analysis of the graduated weld spatter and the stability index data clearly suggests that for either Ar-23%CO₂ or CO₂ shielded welds, short circuit current clamping significantly reduces weld spatter while not appreciably impacting on the welding process stability. It can be concluded that significant reductions in weld spatter are clearly achieved when the current clamp level is maintained at or below 150A for Ar-23%CO₂ shielded and 200A for CO₂ shielded welds. The majority of welds bounded by these clamped levels were carried out under stable welding conditions when using the existing experimental setup.

From a subjective visual comparison between the conventional constant voltage control, the Lincoln STT current control and the alternative control technique it can be concluded that the alternative current control generates much lower levels of spatter than the constant voltage control technique. This level of generated spatter is more consistent with that produced when welding with the Lincoln STT power source under similar welding conditions.

The manual welding trials performed by Thermadyne in the USA were invaluable for independently assessing the performance of the alternative control technique within an environment prone to variation in CTWD and welding travel speed. The manual trials using CO₂ shielding were noted to produce some very clean welds, with very low spatter levels and reasonable weld stability. An extension of these trials which was directed at welding down a gap, was reported to produce a flat bead profile, followed by a good reverse bead with minimal spatter. Similar results were reported during these trials using Ar-23%CO₂ shielding which by comparison produced a finer bead ripple and a cleaner looking weld.
The alternative control technique described in this Chapter has been applied to dip transfer GMAW applications, producing comparable outcomes to more sophisticated control techniques and welding power sources. Experimentally the alternative control technique using short circuit current clamping has been shown to significantly reduce weld spatter without adversely impacting on the weld process stability. However an understanding of the process conditions that influence the short circuit transfer must be investigated further to ascertain their impact on the current clamping methodology before the alternative control technique can be applied over a wider operating range. The investigation of the process conditions that impact on the short circuit droplet transfer and the approach taken to optimize the parameters of the control waveform are both discussed in Chapter 5.
Chapter 5
Alternative Control Parameter Optimization

5.1 Introduction
The alternative control technique proposed in Chapter 4 demonstrated how short circuit current clamping could be utilized to reduce weld spatter in dip transfer GMAW for a limited range of welding conditions. The natural progression of this reported work is the evaluation of the control technique and the impact of short circuit current clamping over a wider range of welding conditions. The alternative control technique is dependent on surface tension mechanisms to achieve the desired short circuit transfer with minimal electromagnetic pinch force, but to extend its operating range it was necessary to identify and assess all the likely short circuit transfer control factors.

This Chapter further reviews issues relating to weld pool oscillation and the electrode melting rate, both of which significantly impact on the synchronization between the short-circuiting event and the weld pool motion, and therefore on the regularity of the droplet transfer. A study of the weld pool oscillation is presented with a focus on ascertaining the mode of weld pool oscillation normally encountered in dip transfer GMAW and therefore the most appropriate equation for calculations. An extension of this work relates the weld pool oscillation with short circuit current clamp levels and based on these results an optimum condition for short-circuiting was devised to enable the use of a minimal level of current clamp.

An analytical model of the arcing period and the electrode melting rate is discussed with simulation results demonstrating its usefulness in the derivation and assessment of optimum arcing parameters based on the alternative current control waveform. Experimentally derived results from welding trials performed over a wide operating range validate the model and the approach taken towards optimization.

During experimental work to assess the alternative control technique, various process irregularities were identified which impacted on either the short circuit or arcing period. A brief overview of the investigations and the control and monitoring techniques that were developed to address these issues are described along with their evaluation and impact on the welding process.
For clarity the discussion and the experimental results have been combined for the various sections.

5.2 Impact of Weld Pool Oscillation and Electrode Melting Rate

Fundamental to weld stability and spatter reduction in the dip transfer GMAW process is the synchronization between the weld pool oscillation and the short-circuiting event. As stated in Chapter 2 it has been suggested by some authors [13, 22] that maximal process stability is achieved when the short-circuiting frequency ($f_s$) and the oscillation frequency of the weld pool ($f_{osc}$) are synchronized such that the short-circuiting frequency is equal to the oscillation frequency of the pool. Even though work presented later in this Chapter questions the above hypothesis the identification of optimum synchronization conditions for the short-circuiting droplet is crucial.

While knowledge of the weld pool oscillation is important, the synchronization of the short-circuiting event is more readily achieved through the control of the electrode melting rate. Therefore further assessment of the alternative control technique and the optimization of the dip transfer GMAW process requires some investigation into the impact of weld pool oscillation and the electrode melting rate on the synchronized short-circuiting event.

5.3 Weld Pool Oscillation

As already stated the synchronization between the short-circuiting droplet and the weld pool motion has a significant impact on the droplet transfer. It is suggested by Lancaster [16] that spatter minimization is realized by forming the molten bridge as close to the electrode axis as possible. To examine the transfer process more thoroughly a study of weld pool behaviour was carried out which incorporated an experimental program. The various phases to this study are reported in the following.

5.3.1 Experimental Setup

Welding trials were carried out in dip transfer GMAW using the alternative control technique and the experimental set-up described in Chapter 3 with the UOW research 400A inverter power source. Bead on plate (BOP) welds of 100mm length were produced on 250×50×5mm mild steel plate using a CO$_2$ shielding gas at 18 litres/min.
The electrode wire was 0.9mm diameter mild steel, which conformed to ER70S-6 AWS specification. The welding torch was stationary and fixed in a vertical position with a 12 mm extension between the contact tip to work-piece. The work-piece was secured to a movable bed, with the travel speed and wire feed rate as specified in Tables 5.1 & 5.2.

5.3.2 Weld Pool Geometry
The derivation of the weld pool oscillation as discussed in Chapter 2 is generally based on the weld pool geometry. For welding applications using a traversing heat source the weld pool is normally elongated in shape as illustrated in Figure 5.1 with the degree of elongation largely dependent on the heat source’s travel speed.

![Figure 5.1. Weld Geometry for a Traversing Heat Source](image)

To calculate the weld pool oscillation frequency of an elongated weld pool it is suggested by Xiao and Den Ouden [25] that an equivalent pool width must be estimated which corresponds to the diameter of a circular pool with an equivalent surface area. In practice however the weld pool surface will differ from an ideal circular elongation and instead resemble a profile similar to that of the shaded region in Figure 5.1. If it can be assumed that the area of the actual weld pool profile is approximately 95% of the ideal elongation then the following equation can be utilized to define the equivalent pool diameter.

$$De = W \sqrt{\frac{C_E - 1}{0.263 \pi} + 0.95}$$  \hspace{1cm} (5.1)

where $W$ is defined as the width of the elongated pool and $C_E$ is the ratio of elongation as a function of the width. This equation of the equivalent pool width can be applied to Equation 2.6 for a more accurate calculation of the weld pool oscillation frequency. Equations 2.6 & 5.1 are utilized in the study of the weld pool oscillation presented later in this Chapter. While the calculated oscillation frequency provides useful information of the weld pool oscillation the equation still needs to be validated against actual recorded weld pool oscillations.
5.3.3 Identification of Weld Pool Oscillation Characteristics

Photographic images of the dip transfer welding process were captured using the digital photographic system and layout described in Section 3.3.2 to identify the mode and characteristics of the weld pool oscillation for the specified experimental setup. A Xenon flash unit provided a controlled front illumination source for the welding process. The triggering of a Pulnix digital line scan camera was synchronized to the welding process through the control DSP digital I/O and the customized process control software. Digital images were captured at pre-selected timed intervals of the arcing period. As only one digital image per weld run was possible, numerous weld runs were performed to enable the compilation of a sequence of arcing period images which could be considered representative of the weld pool’s oscillation characteristics. An inherent 400µs time delay between the software generated trigger pulse and the Xenon flash unit is evident in the compiled timed events displayed in Figure 5.2. Welding parameters and the shielding gas selection were dictated by the need for unambiguous weld pool motion. The selected welding parameters are detailed in Table 5.1.

<table>
<thead>
<tr>
<th>$I_{arc-pk}$ A</th>
<th>$I_{arc-bkd}$ A</th>
<th>$T_{arc}$ ms</th>
<th>$T_{sc-wet}$ ms</th>
<th>$I_{sc-clp}$ A</th>
<th>WFR m/min</th>
<th>Tr.Spd mm/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>20</td>
<td>1.5</td>
<td>0.75</td>
<td>200</td>
<td>5.32</td>
<td>335</td>
</tr>
</tbody>
</table>

The following images are representative of specified time intervals within the arcing period for the dip transfer GMAW process when the welding travel speed is 335 mm/min. The time is taken from the moment the re-established arc is detected.

![Images](a) 0.4 ms  
(b) 1.9 ms  
(c) 3.4 ms
The above image sequence highlights the weld pool mode 2 oscillation characteristic for an arc located asymmetrical to the weld pool. The sequence of weld pool motion is described as follows: (a-b) the weld pool under the influence of the arcing current pulse is depressed with the motion of molten metal directed towards the lagging edge of the weld pool, (c) the intensity of the arc light reduces as the arcing current decreases towards background with the motion of molten metal still directed towards the lagging edge of the weld pool, (d-g) the minimal intensity of arc light suggests the arcing current is at background, a transition in the oscillation cycle has occurred with the motion of molten metal directed towards the leading edge of the weld pool, (h-i) a transition in the oscillation cycle has occurred with the motion of molten metal now directed towards the lagging edge of the weld pool to complete the oscillation cycle.

An approximation of the weld pool oscillation frequency based on the weld pool geometry and Equations 2.6 and 5.1 suggest a mode 2 oscillation period of 15-16ms. For this example the accuracy of the estimated oscillation period will be limited by the reproducibility of arcing conditions that can be achieved with the welding process during image capture. The results do however provide some insight into the characteristic behaviour of the weld pool during dip transfer GMAW.
5.3.4 Validation of the Weld Pool Oscillation Period

To validate the work presented in Section 5.3.3 it was necessary as part of the study into the weld pool oscillation behaviour to capture a sequence of images that related to the same arcing period. High-speed filming of the dip transfer welding process was performed with the intention of identifying and validating the reported mode of weld pool oscillation, the actual oscillation frequency and to verify these observations against the calculated oscillation frequency discussed in Sections 2.3 & 5.3.2 for known weld pool geometries. Laser backlighting as discussed in Section 3.3.3 provided the controlled illumination source for the filming process.

Welding parameters and the shielding gas selection were dictated by the need for an operational environment whereby the arcing period generally exceeded the assumed weld pool oscillation period. The constricted CO₂ arc force provided the excitation mechanism for unambiguous weld pool motion. The selected welding parameters are detailed in Table 5.2.

<table>
<thead>
<tr>
<th>$I_{arc-pk}$ A</th>
<th>$I_{arc-bkd}$ A</th>
<th>$T_{arc}$ ms</th>
<th>$T_{sc-wet}$ ms</th>
<th>$I_{sc-clp}$ A</th>
<th>WFR m/min</th>
<th>Tr.Spd mm/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>30</td>
<td>1.75</td>
<td>0.75</td>
<td>300</td>
<td>4.5</td>
<td>290, 335, 382</td>
</tr>
</tbody>
</table>

The following images which were captured with a camera frame speed of 4000 pps are representative of the dip transfer GMAW process with a welding travel speed of 382 mm/min. Each image contains the captured frame prior to and after the specified time interval of the arcing period.

**Welding Direction**

![Image](image1.png)  
**a) 0ms**

![Image](image2.png)  
**f) 8ms**
Figure 5.3. Weld pool mode 2 oscillation.

The captured image sequence highlights the mode 2 oscillation characteristic for an arc located asymmetrical to the weld pool. The sequence of weld pool motion is described as follows: (a) re-establishment of the arc upon the molten bridge rupture, with the weld pool at equilibrium, as yet not significantly disturbed, (b-c) the molten pool under the influence of the arcing current pulse is depressed, with motion of the molten metal directed towards the trailing edge, some disturbance by the arc force initially triggering minor mode 1 oscillation at the leading edge of the pool which seems to be independent of the main pool oscillation, (d) the arcing current is reducing as evidenced by the reduced arc light intensity with motion of the molten metal still directed towards the trailing edge, (e) the arcing current is at background as evident by the minimal arc light
intensity, a transition in the oscillation cycle has occurred with the motion of the molten metal now directed towards the leading edge, (f) an increase in profile at the leading edge signifies further forward motion of molten metal, (g) a transition in the oscillation cycle has occurred with the motion of molten metal now directed towards the trailing edge, (h) further reduction in profile at the leading edge, the motion of molten metal is directed towards the trailing edge, (i) further reduction in profile at the leading edge, further motion of molten metal directed towards the trailing edge, (j) initial mode 2 oscillation cycle completed, oscillation profile similar to (a).

5.3.4.1 Calculation of the Weld Pool Oscillation Frequency
The weld pool geometry and in particular the width and elongation of the pool was measured and recorded for welds performed for this study. The oscillation frequencies were calculated for mode 1 & 2 oscillation characteristics using Equation 2.5 & 2.6, the equivalent weld pool diameter $D_e$ defined by Equation 5.1, assuming a surface tension of 1 N/m and a density of $7.0 \times 10^3$ kg/m³ [13]. The calculated data is recorded in Table 5.3 which provides a comparison between the two oscillation modes with the results verified against the weld pool oscillation period derived from the high-speed film.

Table 5.3. Tabulated weld pool data.

<table>
<thead>
<tr>
<th>No.</th>
<th>Trav. Speed mm/s</th>
<th>Pool Const $C_E$</th>
<th>Pool Width mm</th>
<th>Pool $D_e$ mm</th>
<th>$f_{osc}$ Mode1 Hz</th>
<th>$T_{osc}$ Mode1 ms</th>
<th>$f_{osc}$ Mode2 Hz</th>
<th>$T_{osc}$ Mode2 ms</th>
<th>$T_{osc}$ Film ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>290</td>
<td>1.4</td>
<td>6.6</td>
<td>7.9</td>
<td>99.41</td>
<td>10.1</td>
<td>57.43</td>
<td>17.4</td>
<td>16.5-17.3</td>
</tr>
<tr>
<td>2</td>
<td>335</td>
<td>1.44</td>
<td>5.7</td>
<td>6.9</td>
<td>121.78</td>
<td>8.2</td>
<td>70.36</td>
<td>14.2</td>
<td>13.0-14.0</td>
</tr>
<tr>
<td>3</td>
<td>382</td>
<td>1.55</td>
<td>5.2</td>
<td>6.6</td>
<td>130.18</td>
<td>7.7</td>
<td>75.21</td>
<td>13.3</td>
<td>12.0-13.0</td>
</tr>
</tbody>
</table>

An analysis of the high-speed film from this series of dip transfer GMAW welding trials provides some insight into the impact of the traversing heat source on the weld pool oscillation behaviour. For welds performed with a travel speed of 290 mm/min the weld pool oscillation was predominately characterized by mode 2 oscillation, with the existence of mode 1 and 2 oscillation observed at the leading edge of the weld pool. The existence of mode 1 oscillation was particularly evident after the transition from pulse to background arcing current ($I_{arc-pk}$ to $I_{arc-bkd}$). Alternatively welds carried out with travel speeds of 335 mm/min and above, exhibited mode 2 oscillation characteristics with minimal indication of mode 1 oscillation at the leading edge of the weld pool.
Based on these initial observations for the described experimental setup, it would seem that a transition in oscillation mode occurs at a welding travel speed less than 290 mm/min, with mode 2 oscillation characteristics more predominant with further increasing travel speed. This argument is also supported by the results of Table 5.3 which suggest that for welding travel speeds above 290mm/min the calculated mode 2 oscillation characteristics offer the strongest correlation to the weld pool oscillation period derived from the high-speed film. Further improvement to the calculated oscillation frequency is expected if a more accurate estimation of the weld pool area is obtained. These findings challenge the approach taken by Hermans, Spikes and den Ouden [13, 22] who in an attempt to identify the relationship between the weld pool oscillation and short-circuiting frequencies utilized a mode 1 oscillation equation to derive the weld pool oscillation frequency with a welding travel speed of 300mm/min.

5.3.5 Optimum Conditions for Short-Circuiting
As stated earlier in Section 2.3, it has been claimed that optimum process stability is achieved when the weld pool oscillation is synchronized with the short-circuiting droplet. Hermans et al [13, 22] suggesting that optimum process stability is realized when the weld pool oscillation frequency matches the short-circuiting frequency. An alternative hypothesis to Hermans et al is suggested here that states: “optimum process stability and droplet transfer is achieved when the droplet to weld pool short circuit coincides with the return motion of the displaced molten metal, at the instant the main body of molten metal is located adjacent to the electrode wire” as illustrated in Figure 5.4.

![Weld Pool Motion Diagram](image)

**Figure 5.4.** Weld pool oscillation cycle - Mode 2.
An analysis of the high-speed filmed welding process suggests that the optimum short-circuiting condition occurs at an interval in the process, which is realized approximately 60% into the weld pool oscillation cycle. For the optimum short-circuiting condition it can be assumed that the influence of surface tension is significant and that only a minimum electromagnetic pinch force is required to achieve the droplet transfer. Based on this assumption only a minimum level of short circuit current clamping is required when an optimum short-circuiting condition is achieved. This hypothesis can be verified from an analysis of the correlation between the short circuit current clamp level and the estimated optimum short-circuiting condition.

5.3.5.1 Experimental Validation of Optimum Short-Circuiting

To enable the proposed new hypothesis of Section 5.3.5 to be investigated further an analysis of welding data was carried out based on the experimental data derived from the alternative control techniques welding trials for CO₂ shielding which are described in Section 4.7. Bead on plate welds were produced using a 0.9mm diameter ER70S-6 copper coated electrode, a \textit{CTWD} range of 8, 12 & 16mm, a wire feed rate of 5.32 m/min and a welding travel speed of 335m/min. A select combination of \( I_{\text{arc-pk}} \), \( I_{\text{arc-bkd}} \) and \( T_{\text{arc}} \) welding parameters were chosen, with the short circuit current clamp optimized by the adaptive controller described in Section 4.5.4. The selected welding parameters used in this analysis are detailed in Table 5.4.

<table>
<thead>
<tr>
<th>( CTWD ) mm</th>
<th>( I_{\text{arc-pk}} ) A</th>
<th>( I_{\text{arc-bkd}} ) A</th>
<th>( T_{\text{arc}} ) ms</th>
<th>( T_{\text{sc-wet}} ) ms</th>
<th>( I_{\text{sc-clp}} ) A</th>
<th>( WFR ) m/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>225-300</td>
<td>20-80</td>
<td>2.25</td>
<td>0.75</td>
<td>Optimized</td>
<td>5.32</td>
</tr>
<tr>
<td>12</td>
<td>200-300</td>
<td>20-80</td>
<td>1.5</td>
<td>0.75</td>
<td>Optimized</td>
<td>5.32</td>
</tr>
<tr>
<td>16</td>
<td>225-275</td>
<td>20-80</td>
<td>1.25</td>
<td>0.75</td>
<td>Optimized</td>
<td>5.32</td>
</tr>
</tbody>
</table>

The weld pool oscillation frequency was calculated for each weld based on the measured pool width, which was derived from an analysis of the weld macro-sections, and the equations and assumptions defined in Section 5.3.4.1. The calculated oscillation frequency is used in the following evaluation.
5.3.5.2 Experimental Results for Optimum Short-Circuiting

As part of the evaluation process for testing the hypothesis an equation was devised which calculates the difference between the arcing period which is punctuated by the short-circuiting event and the hypothesized optimum short circuit event which is a function of the calculated weld pool oscillation frequency. The resultant difference is then normalized as a function of the oscillation period to produce a value which relates to the offset from the optimum as shown in the following equation.

\[
\% T_{\text{opt \ Offset}} = \frac{T_{\text{arc mean}} - (0.6 \times T_{\text{osc}})}{T_{\text{osc}}} \times 100 \quad (5.2)
\]

where \( T_{\text{arc mean}} \) is defined as the mean arcing period. It is believed that examining the correlation between the offset from the optimum as defined by Equation 5.2 and the level of short circuit current clamping achieved for respective short circuit transfers will identify and confirm the optimum short-circuiting event. It is suggested that for dip transfer GMAW an optimum short-circuiting condition should result in the maximizing of surface tension influences which will place minimum dependence on the short circuit current and electromagnetic pinch force to achieve the desired droplet transfer.

Short circuit current clamp levels derived from experimental trials using the adaptive control software described in Section 4.5.4 for CO\(_2\) shielding were extracted for analysis. The clamp regulation criteria for the trials presented in Chapter 4 ensured the short circuit transfer period remained within specified process limits. Based on this data the current clamp level was plotted as a function of the offset from optimum value with the correlation shown in Figure 5.5, where the horizontal axis is expressed as a percentage of the calculated weld pool oscillation period and referenced with respect to the hypothesized optimum short-circuiting condition.

\[\text{Figure 5.5. Optimum short-circuiting boundary.}\]
The current clamp boundary of 200A which is displayed in the above figure is based on the experimentally derived results presented in Section 4.7 for CO₂ shielded welds. An analysis of Figure 5.5 reveals that the short circuit current clamp level only exists within the defined 200A boundary when the short-circuiting event occurs within ±20% of the hypothesized optimum condition. Short-circuiting events outside this boundary required significantly higher levels of short circuit current to achieve consistent droplet transfer.

It should be noted that for some welds the short-circuiting event occurred within the desired optimum range but the adaptive current clamp is marginally higher than the defined 200A boundary. This was commonly observed for cases where the transfer period for larger volume droplets even though transferring under optimum short-circuiting conditions would exceed the adaptive control process limits used in the regulation of the current clamp. Therefore the current clamp is marginally higher than expected to ensure the transfer process was maintained within the prescribed limits. As these welding trials were performed using a CO₂ shielding gas, some process irregularities will exist due to droplet growth and the increased likelihood of rotational droplet behaviour. Such process phenomena significantly impacted on the incidence of excessive transfer periods and droplet repulsion.

The significant impact the weld pool oscillation has on the droplet transfer cannot be over emphasized. However the synchronization of the short-circuiting event and the optimization of the dip transfer GMAW process is more readily achieved through the control of the electrode melting rate, which must be considered when optimizing the weld process.

5.4 Anode Heating and Electrode Melting Rate
The energy distribution within the welding process as discussed in Chapter 2 can be divided into the energy radiated and convected from the arc column, and the energy transferred to the work-piece and the electrode. The heat evolved at the electrode is expended on melting, and secondly on superheating and evaporating the metal in the drop [89].
5.4.1 Anode Heating and Electrode Melting Rate

The electrode melting rate which is a function of anode and electrical resistance heating is significantly influenced by the welding current, shielding gas composition and the electrode diameter, extension and polarity [100, 101]. According to Halmoy [102] the fundamental equation for the wire melting rate model is

$$H_m = H_L + \frac{\varphi \cdot j}{w}$$  \hspace{1cm} (5.3)

where $H_m$ is a constant for the total heat input per unit volume of wire necessary to melt and detach the droplet, $\frac{\varphi \cdot j}{w}$ is the heat produced at the anode end of the wire where $\varphi$ is the work potential constant, $j$ is the current density, $w$ is the wire feed speed and $H_L$ is the sum of the resistive heat input in the electrode extension. The electrode resistance is derived from the resistivity of the electrode material, which is highly temperature dependent for most steels and is considered a function of the current experienced by each elemental length of electrode as it travels from the contact to electrode tip. This relationship is denoted by the following expression, which is integrated over the above mentioned transit time $\tau$ for an element of wire [103].

$$\int_0^\tau j^2(t) \, dt$$  \hspace{1cm} (5.4)

The specific heat content of an element of wire with a resistivity $\rho$ travelling from the contact to the electrode tip is expected to increase at a rate specified by the following equation [103].

$$\frac{dH}{dt} = \rho j^2$$  \hspace{1cm} (5.5)

where the heat content $H$ (or temperature) dependent resistivity $\rho = \rho(H)$. The relationship of resistivity as a function of specific heat for three different steel types is illustrated in Figure 5.6.
It can be seen in Figure 5.6 that the resistivity of the respective steel types increases rapidly with changing heat content below 4 J/mm$^3$ (about 800°C) then commences to level off above this point. An evaluation of the increased heat content during the transit period of the electrode element can be performed by rearranging Equation 5.5 and integrating over the electrode extension from the contact tip $H=0$ to the electrode tip where $H=H_f$. This applied boundary condition must also equate to the transit period as shown in the following equation.

$$f(H_f) = \int_0^{H_f} \frac{dH}{\rho(H)} = \int_0^\tau J^2(t) \, dt \quad (5.6)$$

where the function $f(H_f)$ can be derived experimentally by electrically heating a sample of wire in the manner described in [104, 105]. The relationship of the resistive heat content as a function of $Lj^2/w$ for steady state conditions is illustrated in Figure 5.7, with the greatest interest pertaining to the Si-Mn steel which offers the closest composition to the ER70S-6 electrode wire used in this current work. As can be seen in Figure 5.7 the relationship is linear when the resistive heat content is above 4 J/mm$^3$ and non-linear for values below this [102, 106]. For welding applications where the resistive heat content is above 4 J/mm$^3$ Equation 5.3 can be expressed in the familiar linearized form:

$$w = \frac{1}{H_m + b} \left( \phi j + \rho_1 L j^2 \right) \quad (5.7)$$
This is commonly recognized as the linear melting rate equation:

\[ MR = \alpha I + \beta I \dot{I} \]  \hspace{1cm} (5.8)

For dip transfer GMAW which is a low resistive heating process, the resistive heat content is significantly influenced by the non-linear region of the graph, where the resistive heat input can be derived from the following quadratic regression polynomial [106, 107]

\[ f(H) = \frac{j^2(\tau) I}{w} = C_1 \cdot H_L^2 + C_2 \cdot H_L + C_3 \]  \hspace{1cm} (5.9)

where \( I \) is the electrode extension, \( C_1, C_2 \) and \( C_3 \) are constants with \( C_1 = -194.5 \ A^2 \text{smm}^2/J^2, C_2 = 2402.3 \ A^2/\text{s/mm} \) and \( C_3 = 0 \) for low resistive heating cases.

Using the fundamental melting rate Equation 5.3 and the resistive heat content defined by the non-linear relationship of Equation 5.9, it is possible to model the electrode melting rate for the dip transfer GMAW process.

### 5.5 Modeling the Arcing Period

Central to achieving optimization and control of the short-circuiting event in dip transfer GMAW is the electrode melting rate and burn-back during the arcing period. The impact that arcing current parameters have on the electrode melting rate and the duration of the arcing period may be studied through the development of a melting rate model, which can prove useful for the identification of required arcing current parameters to achieve a desired burn-back per dip cycle.

In the past some authors have proposed melting rate models for dip transfer GMAW, which have been based on the linear melting rate equation referred to earlier in this Chapter. Middleton, Oliveira Santos and Quintino [108] proposed a synergic algorithm, which defined the relationship between the wire melting rate and welding parameters. Ogasawara, Maruyama, Sato, Hida and Saito [79] proposed a melting rate model which defined the relationship between wire feed rate and arcing pulse parameters. However in both instances the models ignore the non-linear relationship between resistive heat content and resistive heat input, which exists with low resistive heating processes. Therefore it can only be assumed that the accuracy of the algorithms derived for these linear models may be uncertain over a wide range of welding conditions.
The melting rate model implemented for this analysis is based on Halmoy's work and in particular uses the quadratic regression polynomial discussed in Section 5.4.1 for low resistive heating applications. Based on Equation 5.9 the resistive heat content is derived by completing the square and solving for $H_L$, producing the following solution

$$H_L = \frac{-C_2 \pm \sqrt{4C_1 \times f(H) + C_2^2 - 4C_1C_3}}{2C_1} \quad (5.10)$$

If the function $f(H)$ at steady state conditions is now expressed in the form $Lj^2/w$ and if the constant $C_3$ is zero for dip transfer GMAW, the equation can be further simplified into the following form for a positive resistive heat content.

$$H_L = -\frac{C_2 + \sqrt{4C_1 \times \left(\frac{j^2(t)}{w}\right) + C_2^2}}{2C_1} \quad (5.11)$$

Based on the electrode melting rate Equation 5.3 and assuming $H_m = 11.1$ and $\phi = 3.5v$ [102], it was found that initial average melting rate estimations were consistently lower than that of the actual wire feed rate. To compensate for this a correction factor $G$, which is dependent on the specific shielding gas, was introduced to the following equation, the value of which was derived experimentally from data extracted from welding trials performed over a range of wire feed rates.

$$MR = \frac{G \cdot \phi \cdot j}{H_m - H_L} \quad (5.12)$$

For this work using Ar-23%CO₂ shielding $G$ corresponded to a value of 1.4, and for CO₂ shielding was 1.64, with the corresponding values of $G \cdot \phi$ being 4.9 and 5.74 for the Ar-23%CO₂ and CO₂ shielding gases respectively. These values were close in value to the 4.7 for the work function of iron quoted in [109] and compare well to the 5.5 used by Huismann and Hoffmeister [110] and the 4.37 and 5.34 by Cuiuri [84] for argon based and CO₂ shielding gases respectively.

The stated result would indicate there are significant errors in the method of estimation even when allowing for experimental error. The introduction of the constant $G$ suggests the impact of anode heating is significantly higher than that indicated by Equation 5.3. Other researchers [139] by contrast have modelled anode heating using the term $\phi + \frac{3KT}{2e} + V_a$ where $\frac{3KT}{2e}$ is the thermal energy of electrons and $V_a$ is the anode fall voltage. Using such an approach would see a value of 5.5v to represent the anode
heating effect, thereby producing a result comparable with that reported. Furthermore the need for varying values of G when using differing shielding gases as suggested by Cuiuri [84] would indicate the electrode melting rate is effected by the shielding gas composition.

This analytical melting rate model was primarily developed for the purpose of simulating the electrode melting rate behaviour when using the alternative control technique. The modelled melting rate was estimated from specified input data relating to the desired wire feed rate, dip frequency, shielding gas and the arcing pulse and background current magnitude. Based on the assumption that arcing pulse parameters would have a significant influence on the determination of optimized welding parameters the arcing pulse width was configured as a model variable. The model control was structured for iterative execution of the melting rate algorithms and the control sequence required the incrementing of the pulse width value followed by the execution of the melting rate algorithms. The subsequent incrementing of the pulse width value was made conditional on a test of the calculated melting rate which is compared to the specified wire feed rate. The control sequence terminated the iteration sequence once the calculated melting rate matched the wire feed rate. The details of the pulse width value, along with the mean and RMS current were outputted for analysis. A simple flow diagram of the iteration process associated with the melting rate model is shown in Figure 5.8.
5.6 Optimization of the Alternative Control Technique

The model assumes that: (1) The resistive heating of the wire element occurs during both the short circuit and arcing periods, (2) The anode heating of the wire electrode occurs only during the arcing period therefore the effective mean arcing current is that averaged over the entire dip cycle, (3) The arc length is considered small in comparison to the electrode stickout; therefore the stickout is assumed equal to the contact tip to work distance (CTWD), (4) The iterative selection of arcing parameters is valid only when the melting rate and wire feed rate are equal, and (5) The short circuit transfer time is estimated from experimentally derived empirical data.

Based on this model the optimization of the dip transfer welding process can be studied along with derivations for optimum arcing current parameters.
and travel speed for that work remained fixed. As a consequence of the success of the initial research, further evaluation and welding trials were considered necessary to validate and optimize parameter sets over a broader industry accepted range of wire feed rates and travel speeds, while still utilizing the same electrode wire and shielding gases.

It was envisaged that the arcing pulse parameters would have the most significant impact towards achieving the desired electrode melting at increased wire feed rates. Identifying the relationship between the wire feed rate and the arcing pulse parameters was considered central to the derivation and implementation of a control strategy that could be applied over a wide range of welding conditions. This approach was also considered by Ogasawara et al [79] who experimentally derived a relationship between the arcing current pulse parameters and the wire feed rate that was reported to provide minimal spatter and enable stable droplet transfer. The reported relationship was as follows:

\[ a \text{wfr} + b = \sqrt{I_p^2 \times T_p} \tag{5.13} \]

where \( I_p^2 \) is defined as the current pulse magnitude, \( T_p \) the pulse width duration, while \( a \) and \( b \) are constants. From this work the arcing pulse parameter \( \sqrt{I_p^2 \times T_p} \) was seen to form a linear relationship with the wire feed rate. However it is widely accepted that electrode melting is a function of both anode heating which is derived from the current (I) and resistive heating derived from the current squared (I^2). The origin of this experimentally derived relationship was therefore investigated further.

Initial welding trials using the alternative control waveform with Ar-23%CO₂ and CO₂ shielding gases were carried out over a range of wire feed rates. An examination of the experimental data revealed the selection of arcing pulse parameters based on the \( \sqrt{I_{pk}^2 \times T_{arc}} \) relationship identified by Ogasawara et al produced a value of mean current (and therefore anode heating) which also linearly increased with wire feed rate when using the control waveform, thereby validating the relationship.

The stated relationship of Equation 5.13 however, will vary with shielding gas, electrode wire size, CTWD and resistivity. This fact was also recognized by Ogasawara et al who suggests that larger wire extensions will require a decrease in the specified
pulse width to reduce the electrode melting rate in order to maintain optimized transfer conditions.

5.6.1 Parameter Selection

As discussed earlier in Section 5.2 the optimization of the dip transfer welding process is achieved when synchronization exists between the weld pool motion and the short-circuiting event, with welding parameters selected specifically to achieve such a condition.

The initial focus of this work was to identify welding parameters that would provide repeated short-circuiting for a desired synchronization condition. For simplicity it was considered desirable for the welding process to supply relatively consistent levels of heat input to the work-piece and therefore repeatable weld pool synchronization conditions over a range of wire feed rates. The control of the weldment heat input was to be achieved primarily through the incremental increasing of the welding travel speed for corresponding increases in wire feed rate. The specification of such a scenario allowed the model to be used in deriving arcing pulse parameters, which are based on achieving the same predetermined short-circuiting frequency over a range of wire feed rates.

For this work it was thought useful to the analysis if the mean background arcing current could be maintained relatively constant for the specified range of welding trials. It was intended that variations in heat input and mean arcing current would be predominately influenced by the arcing pulse parameters during these trials if the mean background arcing current remained constant. This approach can be more clearly illustrated through a simple review of the familiar rectangular pulse waveform equation

$$I_m = \frac{I_p t_p + I_b t_b}{t_p + t_b}$$  \hspace{1cm} (5.14)

where $I_m$ is defined as the mean arcing current. If the equivalent project symbol notation is transposed into the above equation and rearranged the following relationship exists.

$$I_m (T_{arc} + T_{arc-bkd}) = I_{arc-pk} T_{arc} + I_{arc-bkd} T_{arc-bkd}$$  \hspace{1cm} (5.15)
From Equation 5.15 if the arcing period $T_{arc} + T_{arc–bkd}$ and the background relationship $I_{arc–bkd} \cdot T_{arc–bkd}$ remain relatively constant, then by observation it can be seen that the mean arcing current $I_m$ is now linearly related to the arcing pulse parameter $I_{arc–pk} \cdot T_{arc}$. In practice however even though a consistent dip frequency and cycle period over a broad range of wire feed rates may exist the relationship between the arcing period and short circuit transfer time will vary. If the variation in arcing period is not considered significant when compared to the overall length of the arcing period then this simplified approach to parameter selection may still be considered valid.

A simple setup strategy was devised whereby the background arcing current was linearly adjusted with respect to the wire feed rate. The justification for this was that if the total arcing period remains constant then any variation in the pulse width will also be inversely observed in the background arcing period. Therefore if the background arcing period is seen to decrease with wire feed rate then an increase in the background current will effectively compensate for this change and so ensure a relatively consistent $I_{arc–bkd} \cdot T_{arc–bkd}$ term. This compensation action is shown in Figure 5.9 where an increase in wire feed rate results in the variation to the control waveform denoted by the broken line.

**Figure 5.9. Welding parameter configuration with changing WFR.**

It is envisaged from this example that the mean background arcing current should not change significantly if the level of background arcing current increases in accordance with the described setup strategy. The linear relationship that was utilized to determine the background arcing current with respect to wire feed rate for Ar-23%CO$_2$ and CO$_2$ shielding applications is illustrated in Figure 5.10.
5-22

Figure 5.10. Relationship between $I_{arc-bkd}$ and $WFR$

In reality the current pulse does not change instantaneously as the falling edge of the pulse contains a tailing out characteristic to minimize weld pool disturbances. Therefore as the arcing pulse is not truly rectangular in nature some variation in the $I_{arc-bkd} \cdot T_{arc-bkd}$ term is expected over a range of wire feed rate and waveform parameters.

5.7 Modeling and Simulation Results

A melting rate model has been developed based on the control waveform illustrated in Figure 5.9 and Equations 5.11 & 5.12. The primary function of the melting rate model was to estimate the arcing pulse width to achieve the desired electrode melting rate, based on the input parameters relating to the wire feed rate, wire diameter, dip frequency, shielding gas, the arcing pulse current and background current.

Experimentally derived empirical welding data was correlated for the purpose of constructing a relationship between the estimated droplet size and the short circuit transfer period when using Ar-23%CO$_2$ and CO$_2$ shielding gases. The model as discussed earlier in Section 5.5 was designed with iterative features to allow for the adaptive interrogation of incremented values of pulse width until the desired melting rate is achieved for the specified input parameters. The output of the model provided details of the estimated melting rate, the required pulse width $T_{arc}$, the average cycle arcing current defined in Chapter 6 and the RMS current bounded by the transit time $\tau$. 
5.7.1 Analysis of Parameter Selection

The relationship between the arcing pulse parameters and the wire feed rate discussed in Section 5.6 was examined using the melting rate model and the specified range of welding parameters outlined in Table 5.5 for Ar-23%CO₂ and CO₂ shielded welding applications. It was assumed that the weldment heat input, weld pool oscillation frequency and the optimum dip frequency are constant for this series of model simulations.

Table 5.5. Model-simulation parameter set

<table>
<thead>
<tr>
<th>Shielding gas</th>
<th>Dip Freq.</th>
<th>WFR</th>
<th>Wire Diam.</th>
<th>CTWD</th>
<th>I_{arc-pk}</th>
<th>I_{arc-bkd}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar-23%CO₂</td>
<td>85</td>
<td>4.9</td>
<td>0.9</td>
<td>12</td>
<td>235</td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>85</td>
<td>4.8</td>
<td>0.9</td>
<td>12</td>
<td>225</td>
<td></td>
</tr>
</tbody>
</table>

The resultant relationship between the arcing pulse parameter $\sqrt{I_{pk}^2 \times T_{arc}}$ and the wire feed rate, based on the model simulations results for Ar-23%CO₂ and CO₂ shielding are illustrated in Figure 5.11(a) & (b).

As can be seen in Figure 5.11(a) & (b) the correlation between the arcing pulse parameter $\sqrt{I_{pk}^2 \times T_{arc}}$ and the wire feed rate is linear for both Ar-23%CO₂ and CO₂ shielded model simulations with only a difference in gradient for the differing welding conditions. The modelled results are well supported by other reported work [79].
The setup strategy for the background arcing current as described in Section 5.6.1 was evaluated using the melting rate model. The relationship of \( I_{arc-bkd} \times T_{arc-bkd} \) as a function of wire feed rate based on the simulation data was plotted and displayed in Figure 5.12.

![Figure 5.12. Relationship between \( I_{arc-bkd} T_{arc-bkd} \) and WFR](image)

An evaluation of the relationship displayed in Figure 5.12 indicates the proposed strategy to be utilized in the selection of the background arcing current produces a relatively consistent value of \( I_{arc-bkd} \times T_{arc-bkd} \) irrespective of the wire feed rate, with the standard deviation for either shielding gas within 4.5% of the mean. Based on this result the criteria for selecting the background arcing current is considered acceptable for use in further welding trials.

### 5.7.2 Derivation of Arcing Pulse Width

The relationship between the arcing pulse width and wire feed rate was examined for both Ar-23%CO\(_2\) and CO\(_2\) shielding through melting rate model simulations which were performed for the derivation of the arcing pulse width based on the specified input welding parameters outlined in Table 5.6.

### Table 5.6. Welding parameter setup

<table>
<thead>
<tr>
<th>Shield gas</th>
<th>Dip Freq.</th>
<th>WFR</th>
<th>Wire Diam.</th>
<th>CTWD</th>
<th>( I_{arc-pk} )</th>
<th>( I_{arc-bkd} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar-23%CO(_2)</td>
<td>75-85</td>
<td>4-9</td>
<td>0.9</td>
<td>12</td>
<td>235-265</td>
<td>Fig. 5.10</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>85</td>
<td>4-8</td>
<td>0.9</td>
<td>12</td>
<td>225-240</td>
<td>Fig. 5.10</td>
</tr>
</tbody>
</table>
The model simulations for Ar-23%CO₂ shielding were performed assuming an optimum dip frequency of 75 & 85 Hz, for a \( WFR \) of 4-9 m/min. The magnitude of the arcing current pulse \( I_{arc-pk} \) was 235, 250 & 265A, while the background arcing current was derived from Figure 5.10. The model simulation results were correlated with the arcing pulse width plotted as a function of the \( WFR \) as shown in Figure 5.13.

![Figure 5.13. Relationship between \( T_{arc} \) and \( WFR \) for Ar-23%CO₂ (Simulation)](image)

The model simulations for CO₂ shielding were performed assuming an optimum dip frequency of 85Hz, for a \( WFR \) of 4-8m/min. The magnitude of the arcing current pulse \( I_{arc-pk} \) was 225 & 240A, while the background arcing current was derived from Figure 5.10. The model simulation results were correlated with the arcing pulse width plotted as a function of the \( WFR \) as shown in Figure 5.14.

![Figure 5.14. Relationship between Pulse width and WFR for CO₂ (Simulation)](image)

As expected the pulse width is required to increase with wire feed rate to achieve the desired electrode melting rate, and to decrease as the magnitude of the current pulse \( I_{arc-pk} \) increases so as to maintain the arcing parameter \( \sqrt{I_{pk}^2 \times T_{arc}} \) constant. The
relationship highlighting this interdependence is clearly seen for Ar-23%CO₂ shielding in Figure 5.13 and CO₂ shielding in Figure 5.14.

5.8 Welding Validation Experiments

5.8.1 Experimental Setup

Welding trials were carried out in dip transfer GMAW using the alternative control technique and the experimental set-up described in Chapter 3 with the Thermadyne Powermaster 500 inverter power source. Bead on plate (BOP) welds of 100mm length were produced on 250×50×5mm mild steel plate using Ar-23%CO₂ and CO₂ shielding gases at 18 litres/min. The electrode wire was 0.9mm diameter mild steel, which conformed to ER70S-6 AWS specification. The welding torch was stationary and fixed in a vertical position while the work-piece was secured to a movable bed. The Ar-23%CO₂ shielded welding trials were performed using a contact tip to work-piece distance (CTWD) of 12mm over a wire feed rate of 4-9m/min and welding travel speed of 325-420mm/min. The CO₂ shielded welding trials were performed using a CTWD of 12mm over a wire feed rate of 4-8m/min and welding travel speed of 272-400mm/min.

Select combinations of $I_{arc-pk}$, $I_{arc-bkd}$ and $T_{arc}$ welding parameters were chosen. The short circuit current clamp was maintained at an optimized level of 150A and 200A for Ar-23%CO₂ and CO₂ shielding respectively; the selection of these values was based on the experimental results presented in Chapter 4. The ranges of welding parameters used for these welding trials for the respective shielding gases are outlined in Tables 5.7, 5.8 & 5.9.

Table 5.7. Welding parameter range using Ar-23%CO₂ shielding.

<table>
<thead>
<tr>
<th>CTWD mm</th>
<th>$I_{arc-pk}$ A</th>
<th>$I_{arc-bkd}$ A</th>
<th>$T_{arc}$ ms</th>
<th>$T_{sc-wet}$ ms</th>
<th>$I_{sc-clp}$ A</th>
<th>WFR m/min</th>
<th>T.Speed mm/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>235</td>
<td>Fig.5.10</td>
<td>Fig.5.15</td>
<td>0.75</td>
<td>150</td>
<td>4-9</td>
<td>Tab.5.9</td>
</tr>
<tr>
<td>12</td>
<td>250</td>
<td>Fig.5.10</td>
<td>Fig.5.15</td>
<td>0.75</td>
<td>150</td>
<td>5-9</td>
<td>Tab.5.9</td>
</tr>
</tbody>
</table>

Table 5.8. Welding parameter range using CO₂ shielding.

<table>
<thead>
<tr>
<th>CTWD mm</th>
<th>$I_{arc-pk}$ A</th>
<th>$I_{arc-bkd}$ A</th>
<th>$T_{arc}$ ms</th>
<th>$T_{sc-wet}$ ms</th>
<th>$I_{sc-clp}$ A</th>
<th>WFR m/min</th>
<th>T.Speed mm/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>225</td>
<td>Fig.5.10</td>
<td>Fig.5.17</td>
<td>0.75</td>
<td>200</td>
<td>4-8</td>
<td>Tab.5.9</td>
</tr>
</tbody>
</table>
Table 5.9. Welding travel speed in mm/min.

<table>
<thead>
<tr>
<th>Shielding Gas</th>
<th>WFR 4m/min</th>
<th>WFR 5m/min</th>
<th>WFR 6m/min</th>
<th>WFR 7m/min</th>
<th>WFR 8m/min</th>
<th>WFR 9m/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar-23%CO₂</td>
<td>325</td>
<td>363</td>
<td>382</td>
<td>391</td>
<td>400</td>
<td>420</td>
</tr>
<tr>
<td>CO₂</td>
<td>272</td>
<td>305</td>
<td>345</td>
<td>382</td>
<td>400</td>
<td>x</td>
</tr>
</tbody>
</table>

At approximately the midpoint of each weld the oscilloscope and data acquisition system was triggered, recording a 1 second interval of the welding voltage and current. The acquired data was later used to correlate welding process information relating to stability index, short circuit resistance, heat input, mean voltage and current.

5.8.2 Verification of Low Resistive Heating

To assess the validity of the melting rate model and the assumptions made in regards to low resistive heating for dip transfer GMAW, data was extracted from the welding process to confirm that the range of resistive heat input resided within the non-linear region for Si-Mn steel of Figure 5.7, which offers the closest composition to the ER70S-6 electrode wire used in this current work.

Based on the experimental setup and welding trials described in Section 5.8.1 data was extracted from the captured transient voltage and current waveforms of Ar-23%CO₂ and CO₂ shielded welds. The extracted data used in the calculation of $f(H_l)$ with the results of the analysis displayed in Table 5.10 and 5.11. The arcing current in this example refers to the average cycle arcing current defined in Chapter 6.

Table 5.10. Resistive Heat Input using Ar-23%CO₂ shielding gas.

<table>
<thead>
<tr>
<th>Weld No.</th>
<th>Wire Diam Mm</th>
<th>WFR m/min</th>
<th>CTWD mm</th>
<th>Current $I_{arc}$ A</th>
<th>Current $I^2_{rms}$ A</th>
<th>Transit Time $\tau$ s</th>
<th>$f(H_l)$ $L_j^2/\nu$ A²s/mm⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9</td>
<td>5</td>
<td>12</td>
<td>88.98</td>
<td>14412</td>
<td>0.144</td>
<td>5128</td>
</tr>
<tr>
<td>2</td>
<td>0.9</td>
<td>6</td>
<td>12</td>
<td>101.63</td>
<td>18502</td>
<td>0.12</td>
<td>5486</td>
</tr>
<tr>
<td>3</td>
<td>0.9</td>
<td>7</td>
<td>12</td>
<td>117.16</td>
<td>22580</td>
<td>0.103</td>
<td>5747</td>
</tr>
<tr>
<td>4</td>
<td>0.9</td>
<td>8</td>
<td>12</td>
<td>130.76</td>
<td>26270</td>
<td>0.09</td>
<td>5842</td>
</tr>
<tr>
<td>5</td>
<td>0.9</td>
<td>9</td>
<td>12</td>
<td>138.2</td>
<td>30827</td>
<td>0.08</td>
<td>6093</td>
</tr>
</tbody>
</table>
Table 5.11. Resistive Heat Input using CO₂ shielding gas.

<table>
<thead>
<tr>
<th>Weld No.</th>
<th>Wire Diam</th>
<th>WFR</th>
<th>CTWD</th>
<th>Current Arc</th>
<th>Current (I_{rms})</th>
<th>Transit Time (\tau)</th>
<th>(f(\text{HL}))</th>
<th>(L_f^2/v)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mm</td>
<td>m/min</td>
<td>mm</td>
<td>A</td>
<td>A</td>
<td>sec</td>
<td>A²s/mm⁴</td>
<td>A²s/mm⁴</td>
</tr>
<tr>
<td>1</td>
<td>0.9</td>
<td>4.0</td>
<td>12</td>
<td>66.65</td>
<td>10,899</td>
<td>0.18</td>
<td>4848</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.9</td>
<td>4.5</td>
<td>12</td>
<td>76.21</td>
<td>12,644</td>
<td>0.16</td>
<td>5007</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.9</td>
<td>5</td>
<td>12</td>
<td>80.55</td>
<td>14,796</td>
<td>0.144</td>
<td>5265</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.9</td>
<td>6</td>
<td>12</td>
<td>91.46</td>
<td>18,490</td>
<td>0.12</td>
<td>5483</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.9</td>
<td>7</td>
<td>12</td>
<td>103.34</td>
<td>22,735</td>
<td>0.103</td>
<td>5781</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.9</td>
<td>8</td>
<td>12</td>
<td>114.04</td>
<td>27,412</td>
<td>0.09</td>
<td>6096</td>
<td></td>
</tr>
</tbody>
</table>

From this analysis \(f(H_L)\) is seen to vary between \(4.5-6.5 \times 10^3 \text{A}^2 / \text{mm}^4\) for the range of welding trials undertaken. These results as expected place the dip transfer process within the non-linear region of Figure 5.7, where \(H_L\) is non-linearly related to \(f(H_L)\). The above analysis justifies the use of Equation 5.11 in the melting rate model.

5.8.3 Optimized Parameters - Experimentally Derived

As a consequence of the success of the initial welding trials using the alternative control technique further research was now directed towards ascertaining whether the control technique could be applied to dip transfer GMAW applications over a wider industry accepted range of wire feed rates. The primary focus of this work was directed towards identifying process parameters and conditions that significantly impact on weld stability and the generated weld spatter.

A similar evaluation approach to that discussed in Section 4.5.2, which had been adopted for earlier work, was used for the short circuit process monitoring and spatter identification. The basis of the analysis was directed towards visual observation and recorded short circuit time-out and droplet repulsions, the feedback being used in the identification of optimum process conditions and the tuning of welding parameters. The tuning of process parameters was achieved by using a similar approach adopted for the melting rate model. The tuning process required that the magnitude of the arcing pulse current remained fixed, while the pulse width was incrementally increased until stable welding conditions and minimum weld spatter was achieved. Such a condition generally reflected in the low incidence of short circuit time-out and droplet repulsions and was clearly confirmed by visual observation. The background arcing current as discussed in Section 5.6.1 was selected based on the wire feed rate and the relationship outlined in Figure 5.10.
The first set of welding trials was directed at identifying optimum conditions for wire feed rates between 4-9 m/min, using a predetermined $I_{arc-pk}$ magnitude of 235 & 250A with Ar-23%CO$_2$ shielding. For each weld run the transient voltage and current waveforms were captured and data extracted for the analysis of statistical and process information. The experimentally derived relationship between the arcing pulse width and wire feed rate for the predetermined values of $I_{arc-pk}$ is clearly shown in Figure 5.15, with data derived from the melting rate model also applied for comparison. The model-simulated results were based on the existing experimental setup and weld bead geometry, and used optimum dip frequencies of 85Hz & 80Hz for the respective $I_{arc-pk}$ values of 235A & 250A.

![Figure 5.15. Relationship between $T_{arc}$ and $WFR$ for Ar-23%CO$_2$ shielding](image)

As seen in the above graph the required pulse width reduces as the magnitude of the current pulse increases, and increases with wire feed rate. The validity of the model is confirmed from a comparison between the experimentally derived and model-simulated data under similar specified process conditions. Based on this welding trial the experimentally derived arcing parameter $\sqrt{I_{pk}^2 \times T_{arc}}$ was plotted as a function of wire feed rate and is displayed in Figure 5.16.
As reported by Ogasawarra et al [79] and confirmed by the model-simulated results of Figure 5.11, a linear relationship is seen to exist between the arcing pulse parameter and the wire feed rate, which provide stable and optimum welding conditions when using Ar-23%CO₂ shielding. As can be seen in Figure 5.16 this relationship is consistent whether using a current pulse of 235A or 250A for the specified wire feed rate, travel speed and experimental setup. The linear relationship for the 235A current pulse is expressed as:

\[
I_{pk} T_{arc} = 62.963 \times wfr - 62.856 \quad (5.16)
\]

and for the 250A current pulse as

\[
I_{pk} T_{arc} = 67.027 \times wfr - 86.254 \quad (5.17)
\]

The second set of welding trials was directed at identifying optimum conditions for wire feed rates between 4-8 m/min, using a predetermined \(I_{arc-pk}\) magnitude of 225A with CO₂ shielding. With each weld run the transient voltage and current waveforms were captured and data extracted for the analysis of statistical and process information. The experimentally derived relationship between the arcing pulse width and wire feed rate for the predetermined value of \(I_{arc-pk}\) is clearly shown in Figure 5.17, with data derived from the melting rate model also applied for comparison. The model-simulated results based on the existing experimental setup, weld bead geometry, and optimum dip frequencies are displayed in Table 5.12 for an \(I_{arc-pk}\) of 225A.
Table 5.12. Experimentally derived dip frequency for CO₂ shielding trials

<table>
<thead>
<tr>
<th>WFR</th>
<th>4m/min</th>
<th>5m/min</th>
<th>6m/min</th>
<th>7m/min</th>
<th>8m/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dip Freq</td>
<td>85Hz</td>
<td>85Hz</td>
<td>85Hz</td>
<td>80Hz</td>
<td>75Hz</td>
</tr>
</tbody>
</table>

The noted difference in optimum dip frequency for wire feed rates of 7 & 8m/min is largely due to the insufficient travel speed, resulting in greater work-piece heat input, a slightly wider weld pool and lower oscillation frequency.

Figure 5.17. Relationship between $T_{arc}$ and WFR for CO₂ shielding

Similar to the results achieved with Ar-23%CO₂ shielding, the pulse width $T_{arc}$ for CO₂ shielding increases with wire feed rate. A comparison between the experimentally derived and model simulated data confirms the validity of the model under similar process conditions. Based on this welding trial the experimentally derived arcing parameter $\sqrt{T_{pk} \times T_{arc}}$ was plotted as a function of wire feed rate and is displayed in Figure 5.18.

Figure 5.18. Relationship between current pulse parameters and WFR

From an analysis of Figure 5.18 it can be clearly seen that a linear relationship exists between the arcing pulse parameter and the wire feed rate, which provide stable and
optimum welding conditions when using CO$_2$ shielding. The linear relationship when
using a 225A current pulse is expressed as:

$$\sqrt{I_{pk}^2 T_{arc}} = 60.996 \times wfr - 24.178$$  \hspace{1cm} (5.18)

It should be noted that even though the arcing pulse relationship for either shielding gas
is expected to remain valid for the current experimental setup, it is envisaged that this
relationship will change if marked variations in $CTWD$ or work-piece heat input occur.
Both variables potentially impact on the respective electrode melting rate and weld pool
oscillation characteristics.

Though optimization of the welding process has achieved significant benefits in regards
to the welding process stability and the level of weld spatter generated, the optimization
process has been inhibited by inherent process instabilities.

5.9  Investigations into Process Instabilities using CO$_2$ shielding

The experimental welding trials in dip transfer GMAW has led to the identification of a
number of process irregularities, which predominately exist with CO$_2$ shielding. To
adequately assess the alternative control technique when using this shielding gas it was
thought advantageous to identify the source of these irregularities and to determine
whether they could be attributed to natural process phenomena, which would exist
irrespective of the control technique used, or if their occurrence was a consequence of
the applied alternative control technique.

5.9.1  Droplet Instability during the Arcing Period

Observed process irregularities during initial manual welding trials led to the
investigation of a momentary unstable welding condition caused by extended arcing
periods, culminating in excessive droplet growth and on occasion ball spatter. It was
suspected that the constricted localized arc root, commonly associated with a CO$_2$
shielding gas was creating an upward directed deflection of the droplet. The electro-
magnetically induced plasma forces or vapour jets were believed to be acting on the
base of the droplet at the arc root [1, 111], to inhibit the ensuing short circuit. This
phenomenon is clearly illustrated by the diagram in Figure 5.19(a) and the captured
image in Figure 5.19(b).
From the above diagram and image the upward projection of the droplet is clearly seen with the arc root no longer axi-symmetrical to the electrode wire. Instead it is located at an equilibrium point beneath the projected droplet. To verify this hypothesis investigations were carried out to identify the likely causes of the extended arcing periods.

5.9.2 Investigations of Extended Arcing

As a consequence of the observed process irregularities discussed in Section 5.9.1, investigations were carried out for the purpose of developing an understanding of the droplet behaviour and its impact on the arcing period. The primary objective of this investigation was the identification of process conditions which were likely to contribute to the incidence of excess arcing periods, and to devise control strategies which may be used to remedy or minimize their impact on the welding process. An aim of these welding trials was to induce unstable arcing conditions through the promotion of electrode burn-back and large droplet growth. The selected range of parameters used for this initial stage of the investigation is displayed in Table 5.13.

Table 5.13. Extended arcing welding parameters.

<table>
<thead>
<tr>
<th>$I_{arc-pk}$ A</th>
<th>$I_{arc-bkd}$ A</th>
<th>$T_{arc}$ ms</th>
<th>$T_{sc-wet}$ ms</th>
<th>$I_{sc-clp}$ A</th>
<th>WFR m/min</th>
<th>$Tr. Spd$ mm/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>220-250</td>
<td>35-75</td>
<td>1.5</td>
<td>0.75</td>
<td>200</td>
<td>5.0</td>
<td>335</td>
</tr>
</tbody>
</table>

Welding trials were carried out in dip transfer GMAW using the alternative control technique and the experimental setup described in Chapter 3 with the Powermaster 500
inverter power source. Bead on plate welds of 100mm length were produced on 250×50×5mm mild steel plate using CO₂ shielding at 18 litres/min. The electrode wire was 0.9mm diameter mild steel, which conformed to ER70S-6 AWS specification. The welding torch was stationary and fixed in a vertical position with a CTWD of 16mm. The wire feed rate and travel speed were set as per Table 5.13. The peak arcing current \( I_{\text{arc-pk}} \) was varied from 220-250A, while the background arcing current \( I_{\text{arc-bkd}} \) varied from 35-75A.

The process control software was modified to incorporate a threshold detection function which identified an arcing period outside a specified operating range. Upon detecting an extended arcing period, a digital output from the DSP controller triggered a Nicolet 490 storage oscilloscope, which captured transient voltage and current waveforms of the detected event. An analysis of the waveforms of the detected events revealed some instances where the arcing period extended to 85-100ms in duration as opposed to the normal 6-20ms.

5.9.3 Primary Identified Causes of Extended Arcing Period

Photographic techniques which are described in Section 5.9.5.1 were utilized in the investigation to identify process phenomena that may contribute to extended arcing periods. This component of the investigation led to the identification of two primary causes; that of abnormal and excess droplet growth which are described and illustrated in the following section.

5.9.3.1 Abnormal Droplet Growth

The investigation carried out using photographic techniques identified the occurrence of abnormal droplet growth taking place on the sidewall of the electrode instead of the base of the electrode (as is normally the case). This ‘abnormal’ condition it is believed is more likely to occur if a repulsed droplet, rather than detaching, adheres and grows on the electrode sidewall. This described droplet growth was captured and is displayed in Figure 5.20. An analysis of the transient waveforms revealed the occurrence of a droplet repulsion during the short circuit period (-0.032s). The resulting droplet growth on the electrode sidewall is seen to significantly impinge on the arcing period (-0.032– 0.003s).
Even though the illustrated condition may be somewhat extreme it clearly demonstrates the impact that the short circuit droplet repulsion can have on the welding process and in particular when the repulsed droplet attaches and grows on the sidewall of the electrode.

5.9.3.2 Large Droplet Growth

The investigation has also revealed that extended arcing periods are commonly observed with excess droplet growth. This is particularly so when a repulsed droplet remains attached to the electrode, and the subsequent establishment of an arcing period contributes to further droplet growth. The large droplet growth increases the likelihood of unstable upward projected droplet motion and the inhibiting of the ensuing short circuit. This process phenomena is illustrated in Figure 5.21 where the droplet was initially repulsed 0.5ms into the short circuit period, with the resulting re-established arcing period producing large unstable droplet growth.

Even though the described condition is easily identified from transient voltage and current waveforms there is no certainty as to whether the repulsed droplet has remained
attached. Such a condition may be significantly affected by surface tension changes (e.g. due to weld metal composition) or the weld pool oscillation.

5.9.4 Extended Arcing Control Strategy

The feasibility of introducing pre-emptive detection of extended arcing was assessed. An analysis of the captured transient voltage and current waveforms revealed instances where anomalies in the previous dip cycle could account for the ensuing extended arcing period. However many instances did exist where the extended arcing period could not be explained by evident process anomalies in the voltage or current waveform of preceding dip transfer cycles. This analysis led to the conclusion that pre-emptive detection was not feasible for this welding application due to the lack of distinct rules for identification as the effect was more likely resulting from random droplet growth with no characteristic electrical signature.

To minimize the impact an upward projected droplet may have on the welding process, a control strategy was therefore devised and implemented based on monitoring the duration of the arcing period, and upon detection of an extended arcing period, immediately reducing the level of arcing current to a minimum background level. Such action should reduce the current dependent vapour jet force which is acting on the upward projected droplet [1]. This control strategy is illustrated in Figure 5.22 where the control action upon detecting an extended arcing period reduces the arcing current to the minimum background level.

To assess the impact this control strategy has on the stability of the arcing period an evaluation program was devised and implemented.
5.9.5 Evaluation of the Extended Arcing Control Strategy

Based on the experimental setup described in Section 5.9.2, initial welding trials were carried out using the extended arcing period control strategy with the Thermal Arc Powermaster 500 power source. The work was directed towards evaluating the effectiveness of the control strategy when using varying levels of background arcing current $I_{arc-bkd}$. Initially five bead-on-plate welds were deposited using the wire feed rate and travel speed specified in Table 5.13. The peak arcing current $I_{arc-pk}$ was varied between 210-310A, initially starting at 310A and decrementing in value, while the background arcing current $I_{arc-bkd}$ was incremented in 10A steps from 35-75A. For this work the arcing pulse width $T_{arc}$ remained constant at 1.25ms, while the control strategy threshold was set to activate for arcing periods in excess of 20ms.

An analysis of the captured transient waveforms of the detected events revealed the ensuing short circuit generally occurred within 5-10ms of the detected event and the subsequent reduction in arcing current to the minimum background level. In two instances an extended delay of 15ms was noted but generally the ensuing short circuit was observed within 10ms of the reduction in arcing current. It was also noted that the use of background arcing currents from 35-75A did not produce any significant difference to the time between the detected event and the ensuing short circuit. It should however be emphasized that the setting of a 20ms detection threshold placed the detection range marginally outside the normal arcing period and therefore did not necessarily confirm the existence of unstable droplet behaviour.

5.9.5.1 Photographic Investigation of Extended Arcing Control

To expand the investigation the digital line-scan camera system and storage oscilloscope system described in Chapter 3 were synchronized with the process control software, with the experimental test rig for this stage of the work configured for use with the 400A UOW Lab power source. Using this setup the detection of an extended arcing period by the process control software resulted in the synchronized triggering of the digital camera and storage oscilloscope, the oscilloscope pre-triggering ensuring process data acquisition prior to and after the detected event.
5.9.5.1 Analysis at Low Frequency Current Ripple

The investigation involved the use of the 400A UOW Lab power source with the arcing period threshold extended to 30-40ms, which enabled the clear identification of the droplet condition and its impact on the extended arcing period. To increase the likelihood of upward droplet repulsion the background arcing current was maintained at 50-60A, and then reduced to a minimum background current of 15A once an extended arcing period was detected.

A summary of this investigation is outlined in Appendix 3 Table A3.1 along with photographic images and transient waveforms of the detected events. An analysis of each detected event was based on a study of the transient voltage and current waveforms in conjunction with the captured photographic image. The extended arcing period of weld No.6 is illustrated by the captured image and transient waveforms in Figure 5.23(a) & (b).

![Captured image](image1.png) ![Transient Waveform](image2.png)

**Figure 5.23. Extended arcing period**

Analysis of the above waveform reveals the detection of an incipient short circuit during the arcing period, immediately followed by a repulsion of the droplet, as evidenced by the rapid decrease and increase in the voltage. This process anomaly causes the re-establishment of an arcing period and the subsequent excess droplet growth. In this instance the extended arcing period is detected after 40ms with a further 30ms delay before the detection of the ensuing short circuit.

With the arcing period detection threshold set to 30-40ms, the delay between the reduction in arcing current and the ensuing short circuit was seen to regularly extend between 13-32 ms for the majority of detected events, with the delay of the remaining
captured events not extending beyond 10ms. These results highlight the existence of significantly longer time periods between the detected event and the ensuing short circuit than earlier observed using the Powermaster 500 power source with the detection threshold level set to 20ms.

5.9.5.1.2 Analysis at High Frequency Current Ripple

An analysis of the above results revealed the output current ripple frequency of the UOW Lab power source changed from 4kHz to 300 Hz when reducing the background arcing current to a minimum level. The transient waveforms of Figure 5.23 clearly illustrate this variation in the ripple frequency. By comparison a review of the transient waveforms generated by the Thermal Arc Powermaster 500 power source revealed an output ripple frequency in the order of 6 kHz. As the low output ripple frequency of the UOW Lab power source was the result of the power sources setup configuration, minor changes to this setup ensured the current ripple frequency remained at the higher noted value, therefore avoiding anomalies which may occur at lower ripple frequencies.

The experimental work was repeated using the same UOW Lab power source with the above mentioned change in setup. A summary of the investigation is outlined in Appendix 3 Table A3.2 along with captured images and transient waveforms of detected events. Using an arcing period detection threshold of 30-40ms, the delay between the reduction in arcing current and the ensuing short circuit was now regularly observed within 7ms, with only one instance noted where the time period extended to 20ms before the detection of the short circuit. The extended arcing period of weld No. 19 is illustrated by the captured image and transient waveforms in Figure 5.24(a) & (b).
Analysis of the above transient waveforms reveals the short circuit transfer occurred without incident. However approximately 15ms into the arcing period a transient in the arc voltage is noted; the initial rapid rise in voltage is most probably the result of arc wander, with the more gradual excursion in arc voltage highly likely the product of droplet motion.

Based on these limited experimental results it could be suggested that the control strategy is considerably more effective when the current ripple frequency is high. An explanation for this result may relate to the high frequency 'skin' effect in conductors. If the magnitude of the current ripple is high in relation to the mean current then the concentration of the high frequency current to the outer skin of the conductor may have a stabilizing effect on the arc. Yamamoto, Harada and Ueyama [81] allude to this by stating arc rigidity is most stable when the inverter switching frequency is above 10kHz. It would require further research to validate this hypothesis, which was not possible in the current scope of work.

The results from this investigation highlight the existence of a time delay between the reduction in arcing background current and the detection of the ensuing short circuit. This delay period which was generally within 7ms, can be attributed to the weld pool oscillation, which has a significant influence on the ensuing short-circuiting event. This assumption can be verified by considering earlier discussions on weld pool oscillation. For this investigation the weld pool was approximately 7mm wide with an estimated oscillation frequency of 51.5Hz. The detection of the ensuing short circuit after the controlled reduction in arcing current should be realistically expected within half an oscillation cycle, which corresponds in this example to approximately 10ms. Therefore based on the above assumption the ensuing short circuit should occur within 10ms of reducing the arcing current to a minimum background level, which is confirmed by the experimental results.

5.9.5.2 Impact of the Extended Arcing Control Strategy

An interesting aspect of the extended arcing control strategy is that irrespective of the droplet size, no droplet repulsion occurred during any ensuing short circuits once the arcing current had been reduced to a minimum level with the detection of an extended arcing period. This significant impact on the initial short-circuiting condition can be
directly attributed to the reduction in the arcing current to 15A prior to the short circuit event. The control action effectively reduces the electromagnetic forces during the initial short circuit period and therefore the likelihood of droplet repulsion.

Following this investigation a number of conclusions can be made. In many instances the cause of the extended arcing period can be explained from an analysis of the transient voltage and current waveforms preceding the extended arcing period; however numerous occasions were also noted where no obvious cause could be identified. Based on this observation it was not considered feasible to investigate further the implementation of a pre-emptive detection strategy. Alternatively if welding is performed at dip frequencies greater than 40Hz then an arcing period threshold of 20ms can be implemented for most practical welding applications.

5.10 $V_{arc}$ Detection and Short Circuit Transfer Irregularities

During manual welding trials using CO$_2$ shielding the control process was observed to momentarily falter due to premature arc voltage detection. An initial investigation of this condition revealed that the premature detection only sporadically occurred upon the release of the current clamp after a short circuit timeout event. It was noted that the higher current and increasing resistance of the necking bridge contributed to the voltage feedback on occasion exceeding the fixed $V_{arc}$ threshold setpoint which consequently triggered the arc voltage detection. This can be further illustrated by comparing the transient waveforms of Figure 5.25(a) & (b). Figure 5.25(a) illustrates a typical transient voltage response of a short circuit transfer and Figure 5.25(b) the transient voltage response of an extended short circuit period.

![Figure 5.25. Short circuit voltage response for typical and extended transfer periods](image)
As can be seen in Figure 5.25(a) the voltage rapidly decreases upon the establishment of the short circuit. Then upon the completion of the wetting-in period the current increases to a level determined by the current clamp, the voltage feedback linearly responding to the change in short circuit current. During the later stage of the droplet transfer the resistance of the molten necking bridge will increase significantly, culminating in an increased rate of rise in voltage and a near instantaneous increase in voltage upon the molten bridge rupture. Under such operational conditions the measured short circuit voltage is generally maintained well within the arc voltage threshold of 12v for this experimental setup.

In contrast an analysis of Figure 5.25(b) reveals the feedback voltage linearly responds to the increasing current both prior to and after the release of the current clamp. Upon reaching current limit further increases in the feedback voltage are noted which can be attributed to the increasing resistance of the necking bridge. The feedback voltage in this instance is seen to exceed the fixed arc voltage threshold of 17.5v, resulting in the premature detection of the arc voltage and a control transition to the arcing state, which is initially characterized by the introduction of an arcing current pulse. Fortunately in this example, shortly after the premature detected event the molten bridge ruptures and the arc is re-established as noted by the rapid rise in voltage.

These results highlight the existence of irregularities within the short circuit transfer, which tend to impact on the transfer period and the reliable detection of the short circuit to arcing phase transition. Further investigation and identification of these process anomalies was undertaken to facilitate the development of a control strategy which could be used for minimizing the likelihood of premature arc voltage detection.

5.10.1 Short-Circuiting Process Irregularities

An analysis of transient voltage and current waveforms which were captured during welding trials using CO₂ shielding revealed a succession of short transfer periods where the droplet transfer would occur prior to the introduction of the current clamp. The sequence was sporadically interrupted by protracted transfer periods. This initial investigation of the short circuit transfer period focused on the identification of transfer conditions which enhanced or inhibited the droplet transfer.
As part of this investigation random snapshots of the short-circuiting period were captured along with synchronized transient waveforms of the event. The captured data provided information in regards to both uninhibited and protracted droplet transfers. This initial investigation led to the identification of two common process conditions, which are believed to significantly inhibit the droplet transfer. The two process conditions relate specifically to the droplet growth and the synchronization between the short-circuiting event and the weld pool motion. A protracted droplet transfer caused by abnormal droplet growth is illustrated in the following image and the transient waveforms of Figure 5.26(a) & (b).

(a) Captured Image of Transfer  (b) Transient Waveform

Figure 5.26. Extended Short Circuiting Period – Electrode sidewall growth

The image of Figure 5.26(a) was captured 1.9ms into the short circuit period with the overall droplet transfer taking place in 4.25ms. As can be seen in the captured image the droplet growth has occurred on the sidewall of the electrode, with the poorly defined molten bridge seen as a contributing factor to the inhibited metal transfer. Even though it is believed that this condition can be induced by droplet repulsion during prior dip cycles there is no evidence to suggest that this was the cause in this instance. Further analysis of the transient waveform revealed the return to a succession of consistent and uninhibited transfers immediately after the reported protracted transfer period. For comparison the captured image and transient waveform of an uninhibited droplet transfer is shown in Figure 5.27(a) & (b).
In this example the image was captured 1.9ms into the short circuit period with the droplet transfer taking place within 2.5ms and prior to the introduction of the current clamp. As can be seen from the image, the droplet development has occurred at the base of the electrode wire with a well-defined bridge also evident during the transfer.

However not all protracted transfer periods are the result of abnormal droplet growth. As mentioned earlier the weld pool motion and its synchronization with the short-circuiting event can also significantly impact on the short circuit droplet transfer. A protracted droplet transfer as a result of weld pool conditions is illustrated by the captured image and transient waveforms of Figure 5.28(a) & (b).

The image of Figure 5.28(a) was captured 0.9ms into the short circuit period. The protracted droplet transfer taking place after 8.25ms, in which time the short circuit current was increased to 400A to promote the molten bridge rupture.
In this example the protracted short circuit period is the result of insufficient molten metal in the vicinity of the short-circuited droplet to form an adequate meniscus for the promotion of the droplet transfer. Observations reported by Bless [11], show how initial contact between the droplet and molten pool results in surface tension drawing up molten metal from the weld pool to form a meniscus with the droplet. If the droplet is above a critical size, the transfer to the molten pool will then occur under the predominant influence of surface tension. As demonstrated in Figure 5.28(a), if the volume of molten metal in the region of the droplet is insufficient when forming the meniscus the displaced metal will tend to create a cavity within the weld pool. With the influence of surface tension inadequate to promote the droplet transfer the alternative control technique maximizes the electromagnetic pinch force to advance the droplet transfer and ensure minimal disruption to the welding process. This control action is illustrated in the transient waveforms of Figure 5.28(b). The coalescence that occurs during the wetting-in of the droplet to the weld pool due to surface tension is more clearly demonstrated by the following captured image in Figure 5.29.

![Captured image](image1.jpg)  
![Transient waveform of event](image2.jpg)

**Figure 5.29. Impact of surface tension with coalesce of droplet and weld pool**

In this particular example the image of Figure 5.29(a) was captured 0.9ms into the short circuit period. The droplet transfer took place within 3ms and therefore required minimal current clamping. The captured image of the wetting-in phase of the droplet transfer emphasizes the impact surface tension has on the molten pool in the vicinity of the droplet, where during the formation of the meniscus molten metal is clearly displaced from the weld pool.
With a more comprehensive understanding of existing process irregularities during the short circuit transfer it is now possible to develop control strategies that limit the probability of further premature arc voltage detection.

5.10.2 Adaptive $V_{\text{arc\_thres}}$ Control - (Estimated Voltage $V_{\text{est}}$)

As a consequence of the investigation into short circuit transfer process irregularities and the reported premature detection of arc voltage when using a fixed arc voltage threshold, further investigations were carried out to ascertain the most appropriate strategy for the identification of the transition between the short circuit and arcing period. The analysis of transient waveforms of known premature detected events highlighted the need for an adaptable approach to deriving a threshold level which compensated for commonly observed variations in voltage feedback resulting from changing current flow and molten bridge resistance.

Initially the development of the adaptive threshold control was based on the assumption that under a protracted transfer condition the wetting-in of the droplet to the weld pool would be complete by the time the current clamp was released. Therefore any further increase in the short circuit resistance after this event will be a function of the molten bridge necking. Based on this assumption if the minimum short circuit resistance is calculated at the release of the current clamp, then an estimate of the short circuit voltage can be derived from the increasing instantaneous current flow and the wetted-in resistance. Utilizing this approach the estimated short circuit voltage is made insensitive to deviations in feedback voltage, which may result from molten bridge necking or the re-establishment of the arc, and therefore useful for the derivation of an adaptive threshold $V_{\text{arc\_thres}}$. An example of the adaptive threshold control using the estimated short circuit voltage is shown in Figure 5.30 where an offset of 3v was added to the adaptively derived threshold level to provide a buffer and further reduce the likelihood of premature arc detection.
For the example illustrated in Figure 5.30 the $V_{arc\_thres}$ level is initially set to 12v. Upon the release of the current clamp the short circuit voltage rises linearly with respect to the increasing current, with the $V_{arc\_thres}$ level adaptively tuned once the estimated short circuit voltage exceeds the initial 12v threshold. Once current limit is reached the $V_{arc\_thres}$ is held and the adaptive control disabled.

An assessment of the adaptive threshold control was carried out using the alternative control technique in dip transfer GMAW with CO$_2$ shielding. The adaptive threshold control was implemented using the estimated short circuit voltage. The implementation of the threshold control may be seen to provide significant improvements to the welding process stability through the minimization of premature arc voltage detection. However though these improvements were significant some minor incidents of premature arc voltage detection were still noted, leading to the need for further analysis and development of the threshold estimator.

5.10.3 Adaptive $V_{arc\_thres}$ Control - (Estimated $V_{est}$ + Necking $V_{neck}$)

As stated the implementation of the adaptive threshold estimator significantly improved the stability of the welding process when using CO$_2$ shielding. However some incidents of premature arc voltage detection were still noted. Further analysis of the captured events revealed that once the current limit was reached the short circuit voltage continued to rise due to the increasing resistance of the necking molten bridge. This process condition, with the gradual increase in voltage at current limit is illustrated in Figure 5.31.
From the analysis of experimental results the short circuit voltage rate of rise with the current limited at 400A was usually in the order of 0.5 v/ms, which over an extended transfer period leads to premature arc voltage detection if not compensated for in the arc voltage threshold estimator $V_{arc\_thres}$. As the observed rate of rise of the short circuit voltage under these conditions is quite slow, then any increase in voltage resulting from the gradual increase in the necked bridge resistance should be easily tracked. Based on this observation further enhancement to the arc voltage threshold estimator can be achieved by differentiating between the short circuit necking voltage and the rapid voltage rise with the re-establishment of the arc.

This differentiation between the two described voltage conditions was achieved through the low pass digital filtering of the voltage feedback signal, which for this application had a time constant of 0.16ms at a sampling rate of 40µs. The filtered output voltage was then used to form the basis for a filtered necking voltage $V_{neck}$. The tuned digital filter ensured the filter output adequately tracked the short circuit necking voltage but was insensitive to the rapid voltage excursion that was observed at the re-establishment of the arc. The arc voltage threshold estimator was then expanded to incorporate a short circuit voltage estimate and a filtered necking voltage in the following form

$$V_{arc\_thres} = V_{est} + V_{neck} \quad (5.19)$$

The threshold estimator as defined by Equation 5.19 comprises two independent stages. One is the estimated short circuit voltage $V_{est}$ which adaptively regulates the threshold level prior to current limiting, and the other is the filtered necking voltage $V_{neck}$, which regulates the threshold level subsequent to current limiting. The implementation of the adaptive threshold estimator is demonstrated in Figure 5.31.
As can be seen in Figure 5.28 once the current is limited at 400A the filtered voltage feedback signal provides further adaptive regulation of the threshold level, while being insensitive to the rapid rise in voltage resulting from the molten bridge rupture and re-establishment of the arc. A description of the adaptive $V_{\text{arc}}$ threshold control is detailed in Appendix 4.

The analysis and control strategy development discussed in this section has lead to the implementation of an arc voltage threshold estimator which has significantly improved the stability of the dip transfer welding process through the minimization of premature arc voltage detection. During further experimental trials no further incidence of premature arc voltage detection was observed. The investigation has highlighted the inadequacies of a fixed $V_{\text{arc}}$ threshold detection strategy when high short circuit current flow is required to advance the promotion of the molten bridge rupture.

### 5.11 Summary

A natural progression in the development of the alternative control technique, based on the work presented in Chapter 4 is the extended evaluation of the control technique and the impact of short circuit current clamping on the dip transfer welding process over a wider range of wire feed rates. The techniques’ dependence on surface tension mechanisms to achieve the short circuit transfer with minimal electromagnetic pinch influence makes it imperative that a study be carried out to identify and assess optimum short circuit transfer conditions.

The weld stability and spatter reduction in dip transfer GMAW is dependent on synchronizing the weld pool motion with the short-circuiting event, which in turn is
significantly influenced by both the weld pool oscillation and the electrode melting rate (Section 5.2). A study of weld pool oscillation behaviour was carried out which examined the correlation between the calculated and actual pool oscillation frequency. Through the use of the photographic techniques discussed in Chapter 3 both digital and high-speed images of the weld pool oscillation was captured. Based on this work the actual weld pool oscillation frequency was determined and later compared against calculated mode 1 & 2 oscillation frequencies, which were derived from the weld pool geometry. The comparison between the calculated and actual oscillation frequencies indicates that the calculated mode 2 oscillation characteristic offered the closest correlation to the actual weld pool motion. This finding is also supported from the analysis of the high-speed film, which revealed mode 2 oscillation characteristics to be predominant for a heat source traversing faster than 290mm/min (Section 5.3).

An extension to this study considered the impact that weld pool oscillation has on the short circuit transfer. It was hypothesized that if the synchronized short-circuiting event occurred at an interval approximately 60% into the pool oscillation cycle then optimum short circuit transfer could be achieved. To validate this hypothesis the estimated optimum short-circuiting condition was correlated with respect to the adaptively tuned short circuit current clamp levels presented in Chapter 4 for CO₂ shielding. The resultant correlation from this data suggests that minimal current clamping can only be achieved if the short-circuiting event coincides with the hypothesized optimum short-circuiting condition (Section 5.3.5).

A brief study of the electrode melting rate was carried out (Section 5.4) which examined the influence of anode heating and that of resistive heating over the contact to electrode tip transit period. Based on this study an analytical model of the arcing period and electrode melting rate was developed (Section 5.5) for the purpose of simulating the electrode melting rate behaviour for the alternative control waveform. The model algorithms are based principally on Halmoy’s work [102, 104, 106, 107] and the experimentally derived quadratic regression polynomial, which is simplified for low resistive heating applications.

The modeled electrode melting rate is estimated from specified input data relating to wire feed rate, dip frequency, shielding gas, arcing pulse current and background
current. Based on the assumption that arcing pulse parameters would have a significant influence on the determination of optimized welding parameters, the arcing pulse width was configured as a model variable. The model control was structured for iterative execution of the algorithms since the control sequence required the incrementation of the pulse width value followed by the execution of the model's algorithms. Its control sequence is then terminated once the calculated melting rate matches the wire feed rate. The model is able to provide details of the calculated pulse width, along with the mean and RMS current (Section 5.5).

As stated earlier, it was envisaged that the arcing pulse parameters would have a significant impact on the electrode melting rate over a wide range of wire feed rates. The identification of the relationship between the arcing pulse parameters and wire feed rate is potentially useful for the derivation of optimum welding parameters. Based on model simulation and later experimentally derived results, the correlation between the arcing pulse parameters and wire feed rate was identified as a linear relationship which can be expressed as $a \cdot \text{wfr} + b = \sqrt{I_p^2 \times T_p}$, where $a$ & $b$ are welding process-dependent constants (Section 5.6).

Experimental welding trials were performed for both Ar-23%CO$_2$ and CO$_2$ shielding gases, for the purpose of identifying welding parameters that achieve optimum weld stability and minimal weld spatter over a range of wire feed rates. Similar to the approach adopted for the melting rate model (Section 5.7), specific welding parameters were predefined with the arcing pulse width systematically incremented until optimum welding conditions were achieved. This evaluation process was repeated at set intervals of wire feed rate. The assessment of the optimum state was based on visual observation, and the recorded incidence of short circuit timeout and droplet repulsions (Section 5.8).

For analysis, the experimentally derived optimum arcing pulse parameters were plotted as a function of the wire feed rate. For both Ar-23%CO$_2$ and CO$_2$ shielded welding trials, the relationship between arcing pulse parameter and wire feed rate was linear with differing gradients. Further experimentation using Ar-23%CO$_2$ shielding revealed that the relationship is still valid when the process optimization was performed at increased arcing current pulse setpoints under similar welding conditions. As a means of assessing
and validating the melting rate model identical process parameters applied to the experimental trials were input to the model, with the model and experimentally derived pulse width plotted as a function of wire feed rate. An analysis of the results indicates the melting rate model capably predicted the experimental parameters for the specified welding conditions and the analysis confirmed the validity of the model for use in the development of the alternative control technique (Section 5.8).

In the process of performing experimental welding trials to validate the alternative control technique and in particular with CO₂ shielding, various process irregularities were noted during both the short circuit transfer and the arcing period, which seemed to contribute to the extending of these process stages and resulted in momentary weld instability. As a consequence investigations were carried out which focused on the identification of these irregularities and the development of control strategies to minimize their impact on the welding process. Again the use of the digital photographic technique proved invaluable for the capturing and identification of the events. The investigation and analysis led to the development of a new extended arcing control strategy to significantly minimize the impact of excessive arcing periods through the controlled reduction of the arcing current to a minimum background level (Section 5.9). Initial results would suggest that the effectiveness of the extended arcing control strategy is improved when the output current ripple frequency is high.

In addition process irregularities during the short circuit became the impetus for the development of an adaptive arc voltage threshold estimator, resulting in the minimization of premature arc voltage detection (Section 5.10). The implementation of such control strategies resulted in significant improvement to the stability of the dip transfer welding process with no further incidence of premature arc voltage detection observed.

The work described in this Chapter has focused on and demonstrated how the alternative control technique can be applied over a wide range of wire feed rates using both Ar-23%CO₂ and CO₂ shielding. A study of optimum short-circuiting conditions reveals a link to achievable current clamp levels. As control of the dip transfer GMAW process using the alternative control technique has been established, further work is required to evaluate the ability of the technique to control the work-piece heat input and
weld fusion characteristics. An investigation of heat input and weld fusion using the alternative control technique is discussed in Chapter 6.
Chapter 6
Heat Input and Fusion Control

6.1 Introduction
Earlier work presented in Chapters 4 & 5 has demonstrated how the alternative control technique can be utilized to control the dip transfer process and in so doing significantly reduce the generated weld spatter. However as dip transfer GMAW is a fusion welding procedure it is imperative that the control technique is assessed for its ability to control heat input and weld fusion characteristics. This Chapter examines the achieved weld fusion characteristics when using the alternative control technique and discusses various misconceptions associated with heat transfer in dip transfer GMAW.

Heat input control is fundamental to the welding process but is often misunderstood and misrepresented in relation to dip transfer GMAW. In particular the effective heat input in controlled dip transfer is not well documented. This Chapter aims to clarify this misunderstanding through the examination and definition of effective heat input for this specific welding process. An evaluation of the energy consumption in the welding circuit is carried out to demonstrate the need for compensating the circuit resistive elements when assessing heat transfer to the work-piece. This evaluation was the impetus for an assessment of three defined current formats and a focus on current as a control variable.

Based on experimental welding trials reported in Chapter 4 an analysis of the alternative current technique was carried out to assess the ability to control heat input and fusion characteristics in controlled dip transfer GMAW. The experimentally derived results are used to ascertain the relationships between fusion characteristics and welding process variables, weldment heat input, and the defined current formats. Further analysis is also provided detailing a correlation between the average cycle arcing current and weldment heat input, and a comparison of process variables and their impact on bead width and penetration depth.

Later in this Chapter, details of experimental welding trials with coated sheet steel using constant voltage and the alternative control technique are discussed. The evaluation of
the two techniques focuses on fusion control, consistency of reinforcement and weld spatter induced coated surface damage.

### 6.2 Heat Input in Dip Transfer Welding

In spite of the extensive research that has been directed towards the study of heat transfer in the welding process, the methods used in calculating effective heat transfer and welding efficiency differ notably, with varying degrees of accuracy. Tusek, Caloun and Kralj [112] attempted to address the lack of unanimity of terminologies and definitions with respect to arc welding heat transfer by the classification of the various transfer efficiencies associated with the arc welding process. Later work is directed at investigating the melting efficiencies for various arc welding processes using consumable and non-consumable electrodes in conjunction with various shielding media [113, 114]. In spite of this work and that of others discussed in Chapter 2 some confusion still exists with regard to the calculation of effective heat input in dip transfer GMAW. Therefore prior to the evaluation of the alternative control technique and its impact on heat input and fusion control some initial discussion is required to clarify this issue.

As discussed earlier in Section 2.4.3 the difficulties in calculating the effective heat input for dip transfer GMAW are exacerbated by the practice of calculating arc power from the mean voltage and current. These values are generally averaged over the entire dip transfer cycle, with the welding voltage assumed to be representative of the arc voltage.

#### 6.2.1 Calculation of Arc Voltage

With all arc welding processes, the arc voltage is assumed to be the electrical potential that exists between the electrode and the work-piece. For convenience the voltage level indicated by the power source metering is commonly referred to as the arc voltage, which for a given current is directly proportional to the arc length. This approach even though convenient is often incorrect due to the additional resistive components that exist within the welding circuit which generate voltage drops independently of the arc. These voltage drops if kept to a minimum, allow the voltmeter reading to reflect more accurately the actual arc voltage [115].
However for automated welding applications where the evaluation of arc voltage and arc length is a critical component in the control of the arc welding process, more accurate estimation procedures are needed. Dynamic and steady-state models have been developed which predict the arc length in GMAW based on electrode melting rate algorithms [58, 116] or through the use of neural networks [117]. While others [118] have used arc light sensing techniques to demonstrate the correlation between the radiated arc light signal and the arc length.

Alternatively the short-circuiting behaviour of the dip transfer process lends itself to an indirect approach for calculating arc voltage. The approach requires the measurement of the short circuit resistance during the droplet transfer from which an instantaneous estimate of the arc voltage can be derived. A technique for determining the short circuit resistance on-line was investigated by Orszagh, Kim and Horikawa [119] who used this information for determining the electrode extension. The technique used sampled voltage and current data of the short circuit period to calculate a minimum on-line welding circuit resistance. From the instantaneous welding supply voltage $v_s$ and arcing current $i_{arc}$, the on-line arc voltage is calculated using the following equation.

$$v_{arc} = v_s - i_{arc} r$$  \hspace{1cm} (6.1)

where $r$ is the calculated short circuit resistance based on the on-line sampled voltage and current data, with the arc voltage $v_{arc}$ defined as the difference between the welding supply voltage and the welding circuit resistance voltage drop. To enhance the integrity of the on-line resistance measurement a simple recursive IIR linear time-invariant filter was implemented as described by Equation 6.2

$$y(n) = ay(n-1) + bx(n)$$  \hspace{1cm} (6.2)

and is diagrammatically illustrated by the following block diagram.

Figure 6.1. Block diagram of a simple recursive system (From [120])
If project specific variables are substituted into Equation 6.2 the filtered short circuit resistance $r$ can now be expressed as

$$r = a \times r_{prev} + b \times r_{calc}$$  \hspace{1cm} (6.3)

where $r_{prev}$ is defined as the previous filtered output resistance, $r_{calc}$ the current unfiltered resistance measurement, with $a$ & $b$ defined as filter constants. The resulting filtered output resistance is then used in the estimation of the arc voltage.

### 6.2.2 Calculation of Heat Input in Dip Transfer GMAW

For arc welding applications input power can be approximated as the sum of that absorbed by the arc and that by resistive heating [121], which for high resistivity electrodes can account for a significant portion of the total power [122]. The arc power is expected to increase with either arc length or current [123], with the approximated input power distribution simply expressed by the following equation.

$$P_{in} = I \ V_r + I \ V_{arc}$$  \hspace{1cm} (6.4)

where $P_{in}$ is the input power, $I$ the welding current, $V_r$ the welding circuit resistive voltage drop and $V_{arc}$ the arc voltage as defined by Equation 6.1. If this relationship is applied to dip transfer GMAW the distributed input power can be further subdivided to account for the short circuit period where the component of arc power is zero and the arcing period where an arc and resistive power component exists. The input power is now expressed as a function of the short circuit and arcing period as defined by the following equation:

$$P_{in} = \frac{1}{(t_3 - t_1)} \left( \sum_{t_2}^{t_3} v_{arc} \ i_{arc} + \sum_{t_1}^{t_3} v_r \ i \right)$$  \hspace{1cm} (6.5)

where $i$ is the welding current, $t_1$ is the start of the short circuit period, $t_2$ is the start of the arcing period and $t_3$ is the end of the arcing period and the start of the next short circuit. It can be assumed without argument that electrical energy during the welding process will be consumed by all the resistive elements of the welding circuit. Then if the electrical energy consumed by the work-piece resistance is negligible compared to the energy consumed by the arc [28], the energy transfer to the work-piece can be logically
assumed to be primarily a function of the arc power, allowing for Equation 6.5 to be simplified as follows:

\[ P_{in} = \int_{t_1}^{t_3} v_{arc} \, i_0 \, dt = \frac{1}{(t_3 - t_1)} \sum_{t_2}^{t_3} v_{arc} \, i_{arc} \]  

(6.6)

The weldment heat transfer for dip transfer GMAW may now be described by Equation 6.7 when Equation 6.6 is substituted as the power term for Equation 2.8

\[ H_{in} = \frac{\eta}{V} \int_{t_1}^{t_3} v_{arc} \, i_0 \, dt = \frac{\eta}{V} \frac{1}{(t_3 - t_1)} \sum_{t_2}^{t_3} v_{arc} \, i_{arc} \]  

(6.7)

As can be seen the heat transfer to the work-piece in dip transfer GMAW is a function of the average cycle arc power.

### 6.3 Current as a Control Variable

Heat transfer to the work-piece has a significant influence on weld fusion. It may however be preferable for metallurgical reasons to achieve the desired level of fusion with minimum energy input [124]. As discussed in Section 2.4 the control of heat input can be achieved through various means. In particular through the regulation of welding process parameters such as mean current, which for open arc GMAW [27] has a linear correlation to the measured work-piece heat input. This reported relationship would imply that arc power is significantly influenced by current and far less by the arc voltage, which can be defined by the following model:

\[ V_a = V_o + i \, R_a + E_a \, L_a \]  

(6.8)

where \( V_a \) is defined as the arc voltage, \( V_o \) the minimum anode and cathode sheath voltage at zero arc length and no current, \( R_a \) the arc resistance, \( E_a \) the voltage gradient in the arc column in V/mm and \( L_a \) the arc length [103]. Upon examination the model is seen to be comprised of a constant component \( V_o \), with the value of arc voltage significantly influenced by both current and arc length [125, 126, 127, 128].

A study of the GMAW welding process based on modeling and experimentation has revealed that the welding current, arc voltage and electrode extension will influence the weld bead geometry [129]. The welding current is reported to have the greatest
influence on the weld fusion characteristics (which is not unexpected), as an increase in arc voltage at constant current is only achieved through an increase in arc length, which tends to produce increased radiative heat losses, a lowering of the arc efficiency and only a modest increase in heat transfer [130].

These findings are supported by Allum and Quintino's [34] plate fusion model for pulsed GMAW where for given material factors (plate, wire and shielding gas), the dilution behaviour is a function of the product of current $I$ and travel speed $v$. The arcing current logically has the greater influence over the dilution behaviour if the deposition rate and travel speed remain constant.

Such reported results have lead to the development of mass input and bead geometry control strategies which have been directed towards the regulation of the output welding current [131, 132, 133]. Based on the premise that arcing current is the principal variable for controlling heat input in dip transfer GMAW, Westendorp [134] developed a servo adjusted MIG control technique that was integrated with an inverter power source. The concept of the control technique is to regulate the cycle average arcing current during the dip transfer process as expressed by the following equation:

$$I_A = \frac{1}{(t_3 - t_1)} \int_{t_2}^{t_3} i \, dt \quad (6.9)$$

The basis of the algorithm is to control $I_A$ to a predetermined value for each arcing period. The selected value is based on the heat transfer required for the work-piece. The above equation is valid if it is assumed that negligible energy is transferred to the work-piece during the short circuit period.

### 6.3.1 Welding Current Formats

The average welding current is often referred to when considering the parameters for a particular welding application. Even though current flow in dip transfer GMAW occurs during both the short circuit and arcing period, the electrical energy transfer to the work-piece during the short circuit period as well as will be demonstrated later in this Chapter is considered insignificant, with the principle heat transfer occurring during the arcing period.
In practice either of three averaged current formats can be stated when evaluating the welding process. These are the average welding, the average arcing and the average cycle arcing currents, which are respectively defined by Equations 6.10, 6.11 & 6.12. For open arc welding applications where a consistent arcing state exists all three formats define the same current variable; however with dip transfer GMAW this is not the case. Therefore the current format used must be clearly specified in any evaluation, with the specified average current formats defined as follows:

1) Average welding current $I_{ave}$, time averaged over the dip cycle

$$I_{ave} = \frac{1}{t_3 - t_1} \sum_{t_1}^{t_3} i$$  \hspace{1cm} (6.10)

2) Average arcing current $I_{arc-ave}$, time averaged over the arcing period

$$I_{arc-ave} = \frac{1}{t_3 - t_2} \sum_{t_2}^{t_3} i_{arc}$$  \hspace{1cm} (6.11)

3) Average cycle arcing current $I_{arc-cyc}$, time averaged over the dip cycle

$$I_{arc-cyc} = \frac{1}{t_3 - t_1} \sum_{t_1}^{t_3} i_{arc}$$  \hspace{1cm} (6.12)

However before further analysis of arc heat transfer and the defined average current equations an evaluation of the short circuit energy transfer and the use of an estimated arc voltage should be carried out to validate assumptions made in Section 6.2.2.

### 6.4 Evaluation of Short Circuit Energy Transfer

The input energy during the short circuit period is dissipated through the resistive elements that comprise the electrical welding circuit. The majority of the energy is commonly believed to be dissipated in the preheating of the wire electrode, the resistance of which is significantly influenced by the temperature distribution of the electrode’s extension which is typically seen to decrease from 1537°C at the liquid-solid boundary to 70°C at the contact tip [110, 119, 135]. The temperature of the liquid droplet is elevated above this range, with thermal conductive heat flow from the liquid drop to the solid wire significantly affecting the temperature of a small portion of electrode wire in the region of the liquid-solid boundary. The temperature of the electrode wire outside this thermal conductive region is a function of the joule heating.
As in the case of spray transfer GMAW the temperature of the solid wire reaches a quasi-stationary temperature and therefore becomes insensitive to rapid changes in current; for simplicity of analysis a quasi-stationary temperature distribution is assumed. As the resistivity of mild steel is strongly temperature dependent, the wire resistance at any location \( z \) along the wire will depend on the temperature distribution \( T(z) \). Based on temperature distribution curves of electrode extensions [110, 119, 135, 136] the resistivity of the electrode sample lengths was calculated, with an estimate of the total electrode wire resistance derived using the following integral equation.

\[
R(t) = \int_0^L \frac{\rho(T)}{A(z)} \, dl \quad (6.13)
\]

where \( R \) is defined as the total resistance, \( L \) the electrode extension, \( \rho \) the resistivity, \( l \) the wire sample length and \( A \) the cross sectional area at location \( z \). Using this equation for a 0.9mm Si-Mn mild steel wire electrode with a 12mm extension the total electrode resistance was estimated to be 16.4m\( \Omega \).

To verify this analysis a simple experiment was performed for a fixed number of welds run with the electrode extension between 8-18mm. The experimentally derived short circuit resistance was plotted as function of the \( CTWD \), with the relationship between short circuit resistance and \( CTWD \) illustrated in Figure 6.2.

![Figure 6.2. Relationship of short circuit resistance vs \( CTWD \)](image)

The relationship between the short circuit resistance and \( CTWD \) as seen in Figure 6.2 has a linear gradient of 1.453 m\( \Omega \)/mm with an offset of 5.87m\( \Omega \) which closely corresponds to the remaining welding circuit resistive elements. The total short circuit resistance was 23.3m\( \Omega \) and the estimated resistance of the electrode extension 17.4m\( \Omega \) when the \( CTWD \) is 12mm, which compares quite favourably with the 16.4m\( \Omega \) derived
from the assumed temperature distribution. Based on either result the resistance of the electrode extension can be clearly seen to comprise a significant portion of the welding circuit resistance and therefore the primary source of energy consumption during the short circuit period.

The electrical energy consumed during the short circuit period by the electrode extension resistance was calculated using the following equation

\[ H_{SC} = \sum_{t_1}^{t_2} i^2 r t \]  

(6.14)

where \( i \) is defined as the instantaneous current, \( r \) the electrode extension resistance (17.4m\( \Omega \)) and \( t \) the sampling interval. When applied to numerous transient waveforms over their 1 second sampling period, the estimated electrical energy consumed during the short circuit period by the stated electrode resistance is 24.5-28.0 joules. This is insignificant when compared to the weldment input energy of 1500-1800 joules calculated for the arcing period. As a portion of the energy consumed in preheating the electrode extension will transfer to the work-piece by way of the molten droplet it could be concluded that the electrical energy consumed during the short circuit period will contribute minimally to work-piece heating.

### 6.5 Evaluation of Calculated Heat Input with Experimental Setup

Generally the work-piece heat input is calculated from welding voltage and current measurements with little or no consideration given to the equipment setup or differentiation between short circuit and arcing periods. An evaluation of the total process heat input calculated as a function of the measured voltage feedback was carried out and compared to the weldment heat input defined by Equation 6.7, which uses the estimated arc voltage. The focus of this analysis was directed towards assessing the impact welding circuit resistance has on the relationship between weld fusion characteristics and the total and weldment heat input. For the purpose of this evaluation the total heat input was calculated as a function of the mean process power and derived using the following equation, where the measured voltage feedback is assumed to be indicative of the arc voltage with no differentiation made between the short circuit and arcing period.
$$H_{total} = \frac{\eta_i}{\nu} \times \frac{1}{(t_3 - t_1)} \sum_{t_1}^{t_3} \nu \times i \quad (6.15)$$

The welding data used for this analysis is based on the CO₂ shielded welding trials described in Chapter 4, which produced BOP welds on 5mm mild steel plate for CTWD's of 8 & 16mm; the details of these trials are discussed later in this Chapter. The fusion area was plotted as a function of the total (eq.6.15) and weldment heat input (eq.6.7), and displayed in Figure 6.3. Least squares was applied to the data points of both graphs, with lines of best fit drawn to illustrate the relationships.

![Figure 6.3. Relationship of fusion area $A_F$ vs heat input](image)

(a) Fusion area $A_F$ vs $H_{total}$ (Calc.) (b) Fusion area $A_F$ vs $H_{in}$ (Calc.)

An analysis of the above relationships suggest a linear correlation between fusion area and heat input in both Figure 6.3(a) & (b), with the correlation between fusion area and total heat input containing, as expected, the larger zero offset. For further evaluation the resulting relationships were overlaid onto matching axes and displayed in Figure 6.4. To assess the impact of welding circuit resistance on the calculated heat input the method of process control must be considered.

As the alternative control technique was utilized for this experimental work it can be reasonably assumed that the current control waveform characteristics could be readily reproduced with other similar inverter power sources, irrespective of minor differences in the welding equipment setup. The only expected difference is the power source output voltage, which may vary between welding equipment setup when regulating the output current. For this analysis a simulated 5mΩ increase in welding circuit resistance was introduced to the existing welding data. This action effectively simulates an increase in the total consumed process power while contributing nothing to the work-
6-11

piece heat input. Least squares was applied to the recalculated process data with a line of best fit introduced to Figure 6.4 to demonstrate the impact welding circuit resistance may have on the fusion area to heat input relationship. In this Figure the ‘line’ plot represents the weldment heat input relationship of Figure 6.3(b). The ‘asterisk’ plot represents the total heat input relationship of Figure 6.3(a) and the ‘circle’ plot the relationship between fusion area and total heat input with the welding circuit resistance increased by 5mΩ.

![Figure 6.4. Relationship of fusion area $A_F$ vs heat input (Calc.) - Variation in setup](image)

It can be clearly seen in Figure 6.4, that a change of 5mΩ in the welding circuit resistance when using a current control waveform will alter the relationship between fusion area and total heat input. Variation in this relationship is expected for each differing welding setup. In contrast the relationship between fusion area and the weldment heat input remains consistent irrespective of variation in the welding circuit resistance. The relationship is consistent due to the weldment heat input being calculated as a function of estimated arc voltage and power with Equation 6.7 considered appropriate for use with dip transfer GMAW.

6.6 Experimentation and Results

6.6.1 Experimental Results for CO₂ shielding

6.6.1.1 Welding Data and Analysis

This analysis of weld fusion characteristics with heat input is based on the welding trials described in Section 4.7.1 for CO₂ shielding. Bead on plate (BOP) welds of 100mm length were produced on 250×50×5mm mild steel with a 0.9mm diameter mild steel electrode which conformed to ER70S-6 AWS specification wire. The welding torch was stationary and fixed in a vertical position while the work-piece was secured to a
movable bed. This series of welding trials was performed using a \textit{CTWD} of 8, 12 & 16mm at a welding travel speed of 335 mm/min and wire feed rate of 5.32m/min.

Weld samples were cross-sectioned, polished with varying abrasive disc grades and etched using a 2.5\% Nital etchant, which comprises 97.5\% Ethanol + 2.5\% Nitric Acid. Digital images of the macro-sections were recorded for analysis after etching, and image processing software was later used to extract weld fusion characteristics relating to fusion area, fusion depth, bead width, bead area and bead height. A typical macro-section image of a CO$_2$ shielded weld is illustrated in Figure 6.5.

![Figure 6.5. Macro-section image – CO$_2$ Shielding](image)

At approximately the midpoint of each weld the oscilloscope and data acquisition system was triggered, recording a 1 second interval of the welding voltage and current. An analysis of the transient voltage and current waveforms was performed using customized software in a Matlab environment, with the extracted data providing details of the heat input and various current formats.

### 6.6.1.2 Fusion Area vs Heat Input - CO$_2$

Weldment heat input as defined by Equation 6.7 is a function of arc power, welding travel speed and the thermal transfer efficiency of the welding process. The transfer efficiency has been investigated by a number of authors [36, 42, 137], who have reported values between 85-95\% for dip transfer GMAW, where the heat transfer to the work-piece is a function of arc and droplet energy. For the current heat input analysis a conservative thermal transfer efficiency of 0.85 was chosen.

Initially the relationship between the weld fusion area and weldment heat input was examined, with the analysis evaluating the correlation between the measured weld fusion area and the calculated weldment heat input for welding trials using a \textit{CTWD} of 8 & 16mm. The calculated heat input was derived from a thermal transfer efficiency of
0.85, a welding travel speed of 335mm/min and an arc power calculated from the instantaneous power of the transient voltage and current waveforms. The measured weld fusion area was plotted as a function of weldment heat input. The method of least squares was applied to the data points, and a line of best fit drawn to illustrate the relationship, which is shown in Figure 6.6.

![Figure 6.6. Relationship of fusion area $A_F$ vs weldment heat input $H_{in}$ (Calc.)](image)

As can be seen in Figure 6.6 a linear relationship exists between the weld fusion area and the weldment heat input irrespective of variations in $CTWD$ with the correlation having a standard deviation in fusion area of 0.48 mm$^2$. The correlated data reveals an offset in heat input of 102 joules/mm before work-piece fusion is noted. This offset energy as discussed in Section 2.4.4 comprises distributed arc energy, which is consumed by electrode anode and work-piece heating. The remaining energy transferred to the work-piece is also required to overcome work-piece heat losses before achieving weld fusion.

### 6.6.1.3 Fusion Area vs Current - CO$_2$

Following the initial evaluation of weldment heat input the relationship between weld fusion area and current was examined for the three current formats defined in Section 6.3.1. An analysis of the correlation between the measured weld fusion area and the average current values was derived from the welding trial transient waveforms. The weld fusion area was plotted as a function of current. The method of least squares was applied to the data points, with a line of best fit drawn to illustrate the respective relationships which are shown in Figures 6.7, 6.8 & 6.9. Figures (a) illustrate the correlation between fusion area and current for the respective values of $CTWD$ and figures (b) the overall correlation between fusion area and the respective current format.
An evaluation of the data in Figures 6.7, 6.8 & 6.9 would suggest variations in CTWD do impact to some degree on the relationship between the weld fusion area and average welding or average arcing current. By comparison the relationship between weld fusion area and the average cycle arcing current remains quite consistent irrespective of the CTWD. To confirm this observation the standard deviation of the fusion area to current
relationships was calculated for the three defined current formats from the respective lines of best fit, with the resulting standard deviation recorded in Table 6.1.

Table 6.1. Standard Deviation in Fusion Area - CO₂ Shielding

<table>
<thead>
<tr>
<th>Measured Variable</th>
<th>Standard Deviation in Fusion Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Welding Current</td>
<td>0.59 mm²</td>
</tr>
<tr>
<td>Average Arcing Current</td>
<td>0.60 mm²</td>
</tr>
<tr>
<td>Average Cycle Arcing Current</td>
<td>0.43 mm²</td>
</tr>
</tbody>
</table>

The results of Table 6.1 confirm that the average cycle arcing current with a standard deviation in fusion area of 0.43 mm² has the strongest correlation between weld fusion area and current of the three evaluated current formats, irrespective of the CTWD.

6.6.1.4 Current vs Heat Input - CO₂

Current, as previously discussed in Section 6.3, is reported to have a significant influence on weld fusion characteristics. The weld fusion area in dip transfer GMAW is seen to have a strong correlation to the average cycle arcing current. As the weld fusion area also contains a strong correlation to heat input the relationship between the average cycle arcing current and the calculated weldment heat input was examined, with the analysis based on the data derived from the welding trial transient waveforms. The average cycle arcing current is plotted as a function of the weldment heat input. The method of least squares was applied to the data points, with a line of best fit drawn to illustrate the relationship which is shown in Figure 6.10.

Figure 6.10. Relationship of $I_{arc-cyc}$ (Exp.) vs weldment heat input $H_{in}$ (Calc.)

As can be seen in Figure 6.10 the average cycle arcing current exhibits a strong linear correlation to the weldment heat input with a standard deviation in current of 2A. These
results justify the argument presented in Section 6.3 which proposes the use of arcing current as a principal variable in the control of heat input for dip transfer GMAW.

6.6.1.5 Bead Width vs Heat Input - CO₂

The heat transfer to the work-piece as discussed in Chapter 2 has a significant influence on the width of the weld bead. This relationship between weld bead width and heat input was examined, with the analysis evaluating the correlation between the measured weld bead width and the calculated weldment heat input derived from the welding trial data. The measured bead width is plotted as a function of the weldment heat input. As a strong correlation exists between the weldment heat input and the average cycle arcing current, the relationship between bead width and current was also examined. The measured bead width is plotted also as a function of the average cycle arcing current. Least squares was applied to the data points, with lines of best fit drawn to illustrate the respective relationships which are shown in Figure 6.11.

![Figure 6.11. Relationship of bead width vs heat input](image)

An evaluation of the data plotted in Figure 6.11(a) & (b) suggests the bead width has a strong linear correlation to the weldment heat input and average cycle arcing current irrespective of the CTWD. The weldment heat input relationship in this instance has a standard deviation in bead width of 0.26mm, compared to the average cycle arcing current relationship where the standard deviation is 0.27mm as recorded in Table 6.2.

<table>
<thead>
<tr>
<th>Measured Variable</th>
<th>Standard Deviation in Bead Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weldment Arc Heat Input</td>
<td>0.26 mm</td>
</tr>
<tr>
<td>Average Cycle Arcing Current</td>
<td>0.27 mm</td>
</tr>
</tbody>
</table>

Table 6.2. Standard Deviation in Bead Width - CO₂ Shielding
The above results support the argument that the weld bead width is strongly influenced by heat input.

6.6.1.6 Primary Penetration vs Current - CO₂

The primary penetration depth for short arc transfer applications as reported by Murray and Scotti [33] has a strong correlation to the arc heat transfer. They noted that mass transfer does affect the depth of penetration, but the impact of the arc heat transfer is more significant. Essers and Walter [27] have suggested that the heat content of the transferring droplet, which is arcing current dependent, will also influence the primary penetration. Therefore based on these reported observations an increase in current during the arcing period should increase both the heat input and droplet heat content and therefore the depth of primary penetration.

This relationship between primary penetration and arcing current was examined, with the analysis evaluating the correlation between the measured penetration depth and the average and cycle averaged arcing currents derived from the welding trial data. The measured penetration depth is plotted as a function of the average arcing current and the average cycle arcing current as defined by Equations 6.11 & 6.12. The method of least squares was applied to the data points, with lines of best fit drawn to illustrate the respective relationships which are shown in Figure 6.12.

![Figure 6.12. Relationship of penetration depth vs arcing current](image)

An analysis of the above figure indicates the average arcing current has a stronger correlation to the penetration depth than the average cycle arcing current. This observation is well supported by the calculated standard deviation in penetration depth, which for the arcing current relationship is 0.10mm compared to the average cycle
The results of the calculated standard deviation are recorded in Table 6.3.

<table>
<thead>
<tr>
<th>Measured Variable</th>
<th>Standard Deviation in Fusion Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Arcing Current</td>
<td>0.10 mm</td>
</tr>
<tr>
<td>Average Cycle Arcing Current</td>
<td>0.13 mm</td>
</tr>
</tbody>
</table>

This result, which suggests the average arcing current has a stronger correlation to penetration depth than the average cycle arcing current is not unexpected. In the work presented by Murray and Scotti [33] for short arc transfer it was reported that the arc heat transfer has a significant impact on the penetration depth, where for open arc welding the average arcing current is expected to have a similar relationship to the weldment heat input as that which exists with the average cycle arcing current for dip transfer GMAW. Based on these results and the short-circuiting nature of the dip transfer process it could be stated that the arcing periods averaged heat transfer would influence the weld penetration depth.

### 6.6.2 Experimental Results for Ar-23%CO₂ shielding

#### 6.6.2.1 Welding Data and Analysis

This analysis of weld fusion characteristics with heat input is based on the welding trials described in Section 4.7.1 for Ar-23%CO₂ shielding. Bead on plate (BOP) welds of 100mm length were produced on 250×50×5mm mild steel with a 0.9mm diameter mild steel electrode which conformed to ER70S-6 AWS specification wire. The welding torch was stationary and fixed in a vertical position while the work-piece was secured to a movable bed. This series of welding trials were performed using a CTWD of 8, 16 & 20mm at a welding travel speed of 382 mm/min and wire feed rate of 5.32m/min.

Weld samples were cross-sectioned, polished with varying abrasive disc grades and etched using a 2.5% Nital etchant, which comprises 97.5% Ethanol + 2.5% Nitric Acid. Digital images of the macro-sections were recorded for analysis after etching, with image processing software later used to extract weld fusion characteristics relating to fusion area, fusion depth, bead width, bead area and bead height. A typical macro-section image of a Ar-23%CO₂ shielded weld is illustrated in Figure 6.13.
At approximately the midpoint of each weld the oscilloscope and data acquisition system was triggered, recording a 1 second interval of the welding voltage and current. An analysis of the transient voltage and current waveforms was performed using customized software in a Matlab environment, with the extracted data providing details of the heat input and various current formats.

6.6.2.2 Fusion Area vs Heat Input - Ar-23%CO₂

Initially the relationship between the weld fusion area and weldment heat input was examined, with the analysis evaluating the correlation between the measured weld fusion area and the calculated weldment heat input. The calculated heat input was derived using a thermal transfer efficiency of 0.85, a welding travel speed of 335mm/min and an arc power calculated from the instantaneous power of the transient voltage and current waveforms. The measured weld fusion area is plotted as a function of the weldment heat input. A least squares fit was applied to the data points, and a line of best fit drawn to illustrate the relationship, which is shown in Figure 6.14.

As can be seen in Figure 6.14 a linear relationship exists between the weld fusion area and the weldment heat input irrespective of variations in CTWD with the correlation having a standard deviation in fusion area of 0.43 mm². The correlated data reveals an
offset heat input of 91.52 joules/mm before work-piece fusion is noted. An explanation of the offset is given in the discussion of Section 6.6.1.2.

6.6.2.3 Fusion Area vs Current - Ar-23%CO₂

Following the initial evaluation of weldment heat input the relationship between weld fusion area and current was examined for the three current formats defined in Section 6.3.1 with the analysis evaluating the correlation between the measured weld fusion area and average current values derived from the welding trial transient waveforms. The measured weld fusion area is plotted as a function of current. A least squares fit was applied to the data points, with a line of best fit plotted to illustrate the respective relationships which are shown in Figures 6.15, 6.16 & 6.17. Figures (a) illustrate the correlation between fusion area and current for the respective values of CTWD and figures (b) the overall correlation between fusion area and the respective current format.

![Figure 6.15. Relationship of fusion area $A_F$ vs average welding current $I_{ave}$ (Exp.)](image1)

![Figure 6.16. Relationship of fusion area $A_F$ vs average arcing current $I_{arc-ave}$ (Exp.)](image2)
An evaluation of the data in Figures 6.15, 6.16 & 6.17 would suggest variations in $CTWD$ do impact to some degree on the relationship between the weld fusion area and average welding or average arcing current. By comparison the relationship between weld fusion area and the average cycle arcing current remains quite consistent irrespective of the $CTWD$. To confirm this observation the standard deviation of the weld fusion area to current relationships was calculated for the three defined formats from the respective lines of best fit, with the resulting standard deviation recorded in Table 6.4.

<table>
<thead>
<tr>
<th>Measured Variable</th>
<th>Standard Deviation in Fusion Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Welding Current</td>
<td>0.62 mm$^2$</td>
</tr>
<tr>
<td>Average Arcing Current</td>
<td>0.56 mm$^2$</td>
</tr>
<tr>
<td>Average Cycle Arcing Current</td>
<td>0.36 mm$^2$</td>
</tr>
</tbody>
</table>

The results of Table 6.4 confirm that the average cycle arcing current with a standard deviation in fusion area of 0.36mm$^2$ has the strongest correlation between weld fusion area and current of the three evaluated current formats, irrespective of the $CTWD$.

6.6.2.4 Current vs Heat Input - Ar-23%CO$_2$

Based on the discussion of Section 6.3 and the results of Section 6.6.1.4, the relationship between the average cycle arcing current and the calculated weldment heat input was examined, with the analysis based on data derived from the welding trial transient waveforms. The average cycle arcing current is plotted as a function of the weldment heat input. The method of least squares was applied to the data points, with a line of best fit drawn to illustrate the relationship, which is shown in Figure 6.18.
As identified earlier with CO₂ shielded welds the average cycle arcing current exhibits a strong linear correlation to the weldment heat input with a standard deviation in current of 2.58A. These results as also stated in Section 6.6.1.4 justify the argument presented in Section 6.3 which proposes the use of arcing current as a principal variable in the control of heat input for dip transfer GMAW.

6.6.2.5 Bead Width vs Heat Input - Ar-23%CO₂

Heat transfer to the work-piece as reported in Section 6.6.1.5 significantly influences the width of the weld bead. This relationship between weld bead width and heat input was examined for Ar-23%CO₂ welds, with the analysis evaluating the correlation between the measured bead width and the calculated weldment heat input derived from welding trial data. The measured bead width is plotted as a function of the weldment heat input. As a strong correlation exists between the weldment heat input and the average cycle arcing current, the relationship between bead width and current was also examined. The measured bead width is plotted also as a function of the average cycle arcing current. Least squares was applied to the data points, with lines of best fit drawn to illustrate the respective relationships which are shown in Figure 6.19.
An evaluation of the data plotted in Figure 6.19 (a) & (b) suggests the bead width has a strong linear correlation to the weldment heat input and average cycle arcing current, irrespective of the CTWD. The weldment heat input relationship in this instance has a standard deviation in bead width of 0.21mm, compared to the average cycle arcing current relationship where the standard deviation was 0.26mm as recorded in Table 6.5.

Table 6.5. Standard Deviation in Bead Width - Ar-23%CO₂ Shielding

<table>
<thead>
<tr>
<th>Measured Variable</th>
<th>Standard Deviation in Bead Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weldment Arc Heat Input</td>
<td>0.21 mm</td>
</tr>
<tr>
<td>Average Cycle Arcing Current</td>
<td>0.26 mm</td>
</tr>
</tbody>
</table>

The above and reported results in Section 6.6.1.6 for CO₂ shielding support the argument that the weld bead width is strongly influenced by heat input.

**6.6.2.6 Primary Penetration vs Current - Ar-23%CO₂**

Based on the discussion and results of Section 6.6.1.6, the relationship between primary penetration and arcing current was examined, with the analysis evaluating the correlation between the measured penetration depth and the average and cycle averaged arcing currents for Ar-23%CO₂ welds. The measured penetration depth is plotted as a function of the average arcing current and the average cycle arcing current as defined by Equations 6.11 & 6.12. The method of least squares was applied to the data points, with lines of best fit drawn to illustrate the respective relationships as shown in Figure 6.20.
An analysis of the above figure indicates the average arcing current has a stronger correlation to the penetration depth than the average cycle arcing current. This observation is well supported by the calculated standard deviation in penetration depth, which for the arcing current relationship is 0.12mm compared to the average cycle arcing current relationship of 0.15mm. The results of the calculated standard deviation are recorded in Table 6.6.

<table>
<thead>
<tr>
<th>Measured Variable</th>
<th>Standard Deviation in Fusion Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Arcing Current</td>
<td>0.12 mm</td>
</tr>
<tr>
<td>Average Cycle Arcing Current</td>
<td>0.15 mm</td>
</tr>
</tbody>
</table>

This result which suggests the average arcing current has a stronger correlation to penetration depth, compared to the average cycle arcing current is not unexpected for the same reasons as stated in Section 6.6.1.6 for the CO₂ shielding results. Based on these results and those of Section 6.6.1.6 it could be stated that the average heat transfer during the arcing period would influence the weld penetration depth, with the weldment heat input expected to have a weaker correlation.

6.6.3 Experimental Results for Thin Plate

6.6.3.1 Welding Data and Analysis

Welding trials were carried out in dip transfer GMAW using both the alternative control technique and conventional constant voltage control with the experimental setup described in Chapter 3. The welding trials based on the alternative control technique were performed with the 400A UOW Lab research power source, while the
corresponding welding trials using constant voltage control were performed with a Thermadyne 600GMS inverter power source.

Close square butt welds of 100mm length were produced on 1mm Zinc-HI-TEN, G550, Z275 galvanized and G550, A2150 zinalume sheet steel using an Ar-3\%O-5\%CO₂ shielding gas at 18 litres/min. The electrode wire was 0.9mm diameter mild steel, which conformed to ER70S-6 AWS specification. The welding torch was stationary and fixed in a vertical, 15° forehand or 15° backhand angle for a 10mm CTWD. The work piece, which was secured to a movable bed travelled at a speed of 500mm/min, while the wire feed rate was set to 2.56 m/min for the galvanized and 2.36 m/min for the zinalume sheet steel welds.

The selected range of welding parameters of $I_{arc-pk}$, $I_{arc-bkd}$, $T_{arc}$, $V_{ref}$ and Inductance which were used for these trials are detailed in Tables 6.7 & 6.8 for the respective coated sheet steels. For the alternate control technique the short circuit current clamp was maintained above 250A for this range of trials.

### Table 6.7. Galvanized sheet steel welding parameters

<table>
<thead>
<tr>
<th>Work-piece Base Material</th>
<th>Torch Angle</th>
<th>Current Control $I_{arc-pk}$ / $I_{arc-bkd}$ / $T_{arc}$</th>
<th>Constant Voltage $V_{ref}$ / Inductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galvanized 1.0mm</td>
<td>Forehand 15°</td>
<td>200 / 40 / 0.5</td>
<td>14.4 / 50%</td>
</tr>
<tr>
<td>Galvanized 1.0mm</td>
<td>Vertical</td>
<td>200 / 40 / 0.5</td>
<td>14.4 / 50%</td>
</tr>
<tr>
<td>Galvanized 1.0mm</td>
<td>Backhand 15°</td>
<td>200 / 40 / 0.5</td>
<td>14.0 / 50%</td>
</tr>
</tbody>
</table>

### Table 6.8. Zinalume sheet steel welding parameters

<table>
<thead>
<tr>
<th>Work-piece Base Material</th>
<th>Torch Angle</th>
<th>Current Control $I_{arc-pk}$ / $I_{arc-bkd}$ / $T_{arc}$</th>
<th>Constant Voltage $V_{ref}$ / Inductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinalume 1.0mm</td>
<td>Forehand 15°</td>
<td>200 / 25 / 0.65</td>
<td>15.0 / 50%</td>
</tr>
<tr>
<td>Zinalume 1.0mm</td>
<td>Vertical</td>
<td>200 / 25 / 0.65</td>
<td>15.0 / 50%</td>
</tr>
<tr>
<td>Zinalume 1.0mm</td>
<td>Backhand 15°</td>
<td>200 / 25 / 0.65</td>
<td>15.0 / 50%</td>
</tr>
</tbody>
</table>

At approximately the midpoint of each weld the oscilloscope and data acquisition system was triggered, recording a 1 second interval of the welding voltage and current. An analysis of the transient voltage and current waveforms was performed using
customized software in a Matlab environment, with extracted data providing details of heat input and the average cycle arcing current.

Weld samples were cross-sectioned, polished with varying abrasive disc grades and etched using a 2.5% Nital etchant, which comprises 97.5% Ethanol + 2.5% Nitric Acid. Digital images of the macro-sections were recorded for analysis after etching, with image processing software later used to extract weld fusion characteristics relating to the weld fusion area and reinforcement. Digital images were also recorded of the welded sheet steel surface to assess the respective control techniques for coated surface damage attributable to generated weld spatter.

6.6.3.2 Impact of Welding Torch Angle
Generally with all arc welding processes the electrode position, which can be defined as the relationship of the electrode axis with respect to travel direction, travel angle and the adjacent work surface (work angle) will impact on the weld bead shape and penetration. The following diagram illustrates three common welding torch angles.

![Diagram of welding torch angles](Image)

**Figure 6.21. Impact of torch angle welding thick cross-section material**

When the torch orientation changes from the perpendicular to a forehand angle, the molten metal is pushed towards the leading edge of the weld pool, with a decrease in penetration, along with a wider and flatter weld bead often observed when using this torch orientation to weld thicker material. This technique, even though undesirable for some welding applications, is very useful for vertical welds to assist in holding the metal in place.

Conversely with a backhand torch angle the molten metal is pushed away from the leading edge, towards the back of the weld pool where additional weld reinforcement is formed. This torch orientation tends to produce a more convex, narrower and larger
bead. The heat source is concentrated back towards the weld bead where the thermal energy is likely to slow the cooling rate of the weldment and effectively increase the heat input. A shorter arc length results when using this torch orientation which is inclined to affect the absolute values of current and voltage, with a slightly lower voltage setpoint required to achieve a given welding current [138].

Maximum penetration is obtained when the work-piece is in the flat position, and the torch has a backhand dragging angle of 25° from the perpendicular. However in practice a dragging angle of 5° to 15° is normally used for good control of the molten weld pool, while the backhand technique is also known to generally produce a more stable arc, with less spatter deposited on the work-piece [115].

The results in this section are commonly observed when using conventional constant voltage control techniques. However if welding parameters are maintained constant for both voltage and current control techniques then the influence of torch angle on weld fusion characteristics can be examined for the respective control techniques.

6.6.3.3 Fusion Area vs Heat input - Galvanized Sheet Steel
Welding trials were carried out using both constant voltage and the alternative current control techniques with a Ar-3%O-5%CO₂ shielding gas to produce a close square butt weld on 1mm thick galvanized sheet steel. The control techniques were applied with forehand, backhand and vertical torch angles with a CTWD of 10mm.

The relationship between the fusion area and weldment heat input was examined, with the analysis evaluating the correlation between the measured fusion area and the calculated weldment heat input using a thermal transfer efficiency of 85%. As a strong correlation is reported to exist between weldment heat input and the average cycle arcing current, the relationship between the measured fusion area and the average cycle arcing current was also examined. The measured fusion area is plotted as a function of the weldment heat input and average cycle arcing current. The method of least squares was applied to the data points, with lines of best fit drawn to illustrate the respective relationships which are shown in Figure 6.22 (a) & (b).
Figure 6.22. Relationship of fusion area $A_F$ vs heat input - galvanized sheet welds

An evaluation of the limited data points of Figure 6.22(a) & (b) suggests a strong linear correlation exits between the weld fusion area and weldment heat input or average cycle arcing current irrespective of the control technique or torch angle when welding galvanized sheet steel. The standard deviation in fusion area for either relationship is less than 0.1mm$^2$ as shown in Table 6.9.

<table>
<thead>
<tr>
<th>Measured Variable</th>
<th>Standard Deviation in Fusion Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weldment Heat Input</td>
<td>0.097 mm$^2$</td>
</tr>
<tr>
<td>Average Cycle Arcing Current</td>
<td>0.091 mm$^2$</td>
</tr>
</tbody>
</table>

6.6.3.4 Fusion Area vs Heat input - Zincalume Sheet Steel

Using an identical approach to that described in Section 6.6.3.3, welding trials were carried out using constant voltage and the alternate control techniques with a Ar-3%O-5%CO$_2$ shielding gas to produce a close square butt weld on 1mm thick zincalume sheet steel. The control techniques were applied with forehand, backhand and vertical torch angles with a $CTWD$ of 10mm.

The relationship between the weld fusion area and weldment heat input was examined, with the analysis evaluating the correlation between the measured fusion area and the calculated weldment heat input using a thermal transfer efficiency of 85%. As a strong correlation is reported to exist between weldment heat input and the average cycle arcing current, the relationship between the measured fusion area and the average cycle arcing current was also examined. The measured fusion area is plotted as a function of the weldment heat input and average cycle arcing current. The method of least squares
was applied to the data points, with lines of best fit drawn to illustrate the respective relationships which are shown in Figure 6.23.

(a) $A_F$ vs $H_{in}$ (Calc.)

(b) $A_F$ vs $I_{arc-cyc}$ (Exp.)

Figure 6.23. Relationship of fusion area $A_F$ vs heat input - zincalume sheet welds

An evaluation of the limited data points of Figure 6.23(a) & (b) suggests as also reported for galvanized sheet steel welds a strong linear correlation between the weld fusion area and weldment heat input or average cycle arcing current irrespective of the control technique or torch angle when welding zincalume sheet steel. The standard deviation in fusion area for either relationship is less than 0.06mm$^2$ as shown in Table 6.10.

Table 6.10. Standard Deviation in Fusion Area - Zincalume sheet welds

<table>
<thead>
<tr>
<th>Measured Variable</th>
<th>Standard Deviation in Fusion Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weldment Heat Input</td>
<td>0.033 mm$^2$</td>
</tr>
<tr>
<td>Average Cycle Arcing Current</td>
<td>0.058 mm$^2$</td>
</tr>
</tbody>
</table>

The experimental results presented here and in Section 6.6.3.3 suggests the weld fusion area has a strong linear correlation to the weldment heat input and average cycle arc current for dip transfer GMAW, with the results valid irrespective of the control technique used. However even though this relationship is easily recognised there is no certainty that control of the fusion area is maintained once the welding process is exposed to variations in the welding torch angle. To verify this further analysis is required to assess the performance of the constant voltage and alternative control techniques under these welding conditions.
6.6.3.5 Impact of Torch Angle - Welding Galvanized Sheet

The electrode position as discussed in Section 6.6.3.2 does generally impact on the welds bead shape and penetration. Therefore the impact of the welding torch angle on weld fusion characteristics should be considered when evaluating the performance of the alternative control technique. This assessment was performed against a commonly accepted control technique under similar welding conditions. The primary focus of the evaluation was directed towards assessing the ability of the respective control techniques to achieve consistent fusion characteristics.

The initial investigation evaluated the consistency in penetration, fusion area and the average cycle arcing current produced by the respective control techniques when exposed to variations in weld torch angle (while welding galvanized sheet steel). It was observed when welding with the constant voltage control technique the average cycle arcing current varied significantly when exposed to variations in torch angle. A backhand torch angle produced a larger weld fusion area and average cycle arcing current, while a forehand torch angle tended to produce a lower value of average cycle arcing current, with a correspondingly smaller penetration and fusion area.

These noted fusion characteristics when using constant voltage control were however not replicated by the alternative control technique when exposed to similar variations in welding torch angle. Using a consistent set of welding parameters the average cycle arcing current remained relatively constant, producing consistent weld penetration and fusion area irrespective of the torch orientation. The only observed variation was the measured output voltage, which changes with welding conditions while regulating the current output. It was noted that the output voltage was generally higher with a forehand torch and conversely lower for backhand torch angles.

Based on this initial analysis of galvanized sheet steel welds it can be concluded that the alternative control technique achieves more consistent control of penetration and weld fusion area compared to the constant voltage control technique when welding conditions are characterized by variations in torch angle. The macro-sections of welds produced using the alternative control technique with variable welding torch angle are displayed in Figure 6.24.
The above macro-sections are typical of the results achieved when using the alternative control technique to weld galvanized sheet steel. The welding parameters were identical for each weld, with comparable heat input and weld fusion area produced. The images of Figure 6.24(a), (b) & (c) emphasize the consistency in penetration and fusion area achieved when using the alternative control technique with a 15° backhand dragging, a vertical and a 15° forehand torch angle. This can be compared with the results achieved using the constant voltage control technique to weld galvanized sheet steel. The macro-sections of welds produced using the constant voltage control with variable welding torch angle are displayed in Figure 6.25.

The macro-sections shown in Figure 6.25 are typical of results achieved using the constant voltage control technique to weld galvanized sheet steel. The images of Figure 6.25(a), (b) & (c) clearly illustrating the inconsistency in the penetration and fusion area achieved when using this control technique. Figure 6.25(a) illustrates a 15° backhand dragging torch angle with a voltage setpoint of 14v, (b) a vertical torch angle with a voltage setpoint of 14.4v and (c) a 15° forehand torch angle with a voltage setpoint of 14.4v, with a common power source inductance setting of 50%.

Even though the analysis revealed the backhand and vertical torch positions produced similar heat input and fusion area as seen in Figure 6.25(a) & (b) it should be
emphasized that the voltage setpoint used with the backhand torch angle was lower and if set to a similar setpoint value as used for the vertical torch an increase in heat input and fusion area should be observed. Conversely inadequate penetration and fusion area was noted when the torch orientation was changed from the vertical to a forehand angle. Based on this analysis it can be concluded that a backhand torch angle has the greatest impact on penetration and fusion area with a forehand torch angle having the least impact when using constant voltage control to weld galvanized sheet steel. In contrast the impact of torch angle on penetration and fusion area is insignificant when using the alternative control technique.

The inconsistency in penetration due to variation in torch angle when using constant voltage control is further emphasized by images of the weld reinforcement. A comparison of the weld reinforcement images shown in Figure 6.26 demonstrates the differences in consistency of the penetration achieved when using the constant voltage and alternative control techniques with a $15^\circ$ forehand torch angle.

![Weld reinforcement images](image)

**Figure 6.26. Weld reinforcement - galvanized sheet**

Figure 6.26(b) illustrates how more consistent reinforcement was achieved over the length of the weld when using the alternative control technique with a forehand torch angle. This is compared to Figure 6.26(a) where the weld reinforcement is inconsistent when using constant voltage control with a similar forehand torch angle. Even though an increase in weld reinforcement can be achieved with constant voltage control through an increase in the voltage setpoint, the variation in torch angle and its impact on penetration and fusion area highlights the irregularities in weld quality that can be experienced with some voltage control techniques which is not seen when using current control techniques to weld galvanized sheet steel.
The reasons for this consistency in fusion control when using a current control technique can be explained by a number of factors. It has been well documented in earlier sections of this Chapter that the average cycle arcing current has a strong correlation to heat input and has therefore a significant influence on weld fusion characteristics. When using the alternative control technique it was noted that to maintain regulated levels of current as the torch angle varied the output voltage would rise with a forehand torch angle and reduce as the torch orientation rotated towards a backhand position. This observation suggests an increased resistance to current flow when the welding torch position was directed towards the leading edge of the weld pool, which may have been the consequence of an increasing arc length. Conversely with constant voltage control the average cycle arcing current would decrease as the torch orientation rotated from the backhand to the forehand position, with the resulting fusion area confirming this change.

6.6.3.6 Impact of Torch Angle - Welding Zincalume Sheet

The impact of torch angle on weld fusion characteristics when using the alternative control technique to weld zincalume sheet steel was also examined with the control techniques performance assessed against the constant voltage control technique. Initially the investigation as in Section 6.6.3.5 focused on evaluating the consistency in penetration, fusion area and average cycle arcing current for the respective control techniques to variations in the torch angle while welding zincalume sheet steel.

An analysis of the average cycle arcing current and fusion area for this particular set of welding trials revealed that unlike the inconsistent fusion characteristics noted when welding galvanized sheet steel with constant voltage control, the penetration and fusion area did not vary significantly when exposed to similar changes in the torch orientation. Rather the average cycle arcing current was seen to decrease slightly with a backhand torch angle, resulting in a corresponding slight decrease in fusion area. As expected the alternative control technique produced relatively consistent penetration and fusion area irrespective of the torch angle. The macro-sections of welds produced using the alternative control technique with variable welding torch angle are displayed in Figure 6.27.
The macro-sections shown in Figure 6.27 are typical of results achieved using the alternative control technique to weld zinoidalume sheet steel. The welding parameters were identical for each weld, with comparable heat input and fusion area produced. The images of Figure 6.27(a), (b) & (c) emphasize the consistency in penetration and fusion area achieved when using the alternative control technique with a 15° backhand dragging, a vertical and a 15° forehand torch angle. This can be compared with results achieved using the constant voltage control technique to weld zinoidalume sheet steel. The macro-sections of welds produced using the constant voltage control with variable welding torch angle are displayed in Figure 6.28.

The macro-sections shown in Figure 6.28 are typical of results achieved using the constant voltage control technique to weld zinoidalume sheet steel. The images of Figure 6.29(a), (b) & (c) clearly illustrate the consistency in penetration and fusion area achieved when using a 15° backhand dragging, a vertical and a 15° forehand torch angle with identical welding parameters. The voltage setpoint was 15v and the power source inductance 50% for each of the welds. It can be seen from the above results that the penetration and fusion area is not as sensitive to variations in welding torch angle as that observed when welding galvanized sheet steel. The consistent reinforcement achieved over the length of the weld when using the two control techniques is also highlighted in Figure 6.29.
As can be seen in the Figure 6.29(a) & (b) relatively consistent results were achieved irrespective of torch angle or control technique when welding zincoalume sheet steel.

### 6.6.3.7 Spatter and Coated Surface Damage

Weld spatter when welding coated steels can result in significant damage to the coated surface. Therefore the selection of process parameters when welding such materials should not only achieve the desired heat input but also minimize coated surface damage resulting from weld spatter. Based on the limited experimental work with coated steels the alternative current control technique was noted to produce significantly less spatter and coated surface damage than that observed when using constant voltage control. A comparison of the coated surfaces when using the two control techniques to weld galvanized sheet steel is shown in Figure 6.30.

As can be seen in Figure 6.30(a) the damage to the coated surface is significantly worse when using constant voltage control compared to Figure 6.30(b) where the coated surface damage due to weld spatter is minimal when using the alternative control technique. Similar observations were noted whether welding galvanized or zincoalume sheet steels.
6.7 Summary

Heat input and fusion control is a critical measure in the welding process. However in spite of extensive research that has been directed towards the study of heat input, confusion still exists in regards to appropriate methods by which effective heat input can be calculated for dip transfer GMAW. To clarify this confusion a brief review of heat transfer during the dip transfer welding process was carried out resulting in a derivation for effective arc heating in dip transfer. This derivation was based on the assumption that electrical energy transferred to the work-piece during the short circuit period is insignificant, and that the effective heat transfer to the work-piece is a function of arc power averaged over the dip transfer cycle. An evaluation of the electrical short circuit energy transfer to the work-piece later validated the assumptions used in the derivation.

To demonstrate the importance of using an estimate of the arc voltage when assessing heat transfer to the work-piece an evaluation of energy consumption in the welding circuit was carried out. It was confirmed that the electrode wire extension formed a significant portion of the short circuit resistance, and if the energy consumed by the resistive elements of the welding circuit is not compensated for when deriving the arc voltage the relationship between fusion area and heat input will alter for differing welding setups. It is proposed that the use of an online method for calculating short circuit resistance can provide a useful means by which an estimate of the arc voltage and power can be attained.

The evaluation of the voltage distribution in the welding circuit was the impetus for a review of current as a control variable in dip transfer GMAW and the assessment of three defined current formats and their correlation to heat input and fusion characteristics. The relationship between fusion characteristics, heat input and the three current formats, average current, average arcing current and average cycle arcing current were examined. The investigation revealing that weld fusion area and bead width has a strong linear correlation to weldment heat input and the average cycle arcing current. Further investigation confirmed the existence of a strong linear correlation between the average cycle arcing current and weldment heat input. While the average arcing current has a stronger correlation to penetration depth than the average
cycle arcing current. These reported correlations were valid whether using Ar-23%CO₂ or CO₂ shielding.

An analysis of the alternative current technique was performed to assess its ability to control heat input and fusion characteristics in dip transfer GMAW. Experimental welding trials with coated sheet steels were carried out using the alternative control technique and for comparison the constant voltage control technique. The evaluation of the two techniques focused on consistency of fusion control, reinforcement and an appraisal of weld spatter induced coated surface damage. The analysis of the welds and extracted process data revealed the alternative control technique produced consistent fusion, weld reinforcement and minimal weld spatter and coated surface damage irrespective of the coated sheet material or welding torch orientation. In comparison the constant voltage control technique produced fusion and reinforcement characteristics which changed significantly with variations in torch angle when welding galvanized sheet steel, while also generating significantly more weld spatter and coated surface damage.

Based on the results presented in this Chapter it can be concluded that the average cycle arcing current which possesses a strong correlation to heat input can be used in dip transfer GMAW as a process variable for heat input and fusion control. The results presented on coated sheet steel welding suggest the alternative control technique is superior to constant voltage control techniques for achieving consistent weld fusion and penetration when the welding process is exposed to variations in the welding torch orientation.
Chapter 7
Discussion, Conclusion & Recommendations

7.1 Discussion

Some detailed discussion of this work is included in the previous Chapters while the overall results are summarized below:

Previously both voltage and current control techniques for dip transfer GMAW have placed significant emphasis on the use of electromagnetic pinch force to achieve consistent control of the short-circuited droplet transfer. Excessive weld spatter is generated if the short circuit current is not reduced prior to the molten bridge rupture. This performance criteria effectively limits some inverter power source designs to voltage control applications. However if a holistic approach is applied to the control methodology then process de-coupling of the short circuit and arcing period, with independent control of weld spatter and fusion can be achieved without a reliance on short circuit rupture premonition detection or process specific power sources. This allows a control methodology to be designed which operates within the constraints of the equipment design whilst still providing significant process benefits. This thesis aimed to explore these issues and present an alternative approach to controlling the dip transfer process.

In order to perform the research, a power source control system has been designed and constructed for the purpose of developing and testing dip transfer GMAW control techniques for use with conventional primary inverter power sources. Central to the control system is a DSP based controller, which provides an adaptable programmable environment with flexible data exchange with the operator interface. The control system, its isolation interface and the photographic techniques developed for the study of the dip transfer welding process are described in detail in Chapter 3.

The primary aim of this research was to explore the mass and thermal transfer mechanisms associated with dip transfer gas metal arc welding with the overall goal of developing and evaluating novel process control strategies, which place more emphasis
on natural transferring mechanisms such as surface tension to sustain the welding process.

As a result of this work a new current control approach was developed, based on the premise that if a critical size droplet is grown then the short circuit droplet transfer will occur under the influence of surface tension. The new alternative control approach, which is described in Chapter 4, provides de-coupled control of the short circuit and arcing periods. The technique is characterized by the clamping of the short circuit current to minimize weld spatter, and an arcing period which comprises a droplet forming and arc heating phase as the means of controlling electrode burn-back and arc heating.

A simple analytical model of the transfer period using the average bridge pressure and the Bernouli equation for determining flow velocity was developed to analyze transfer characteristics under short circuit conditions. The model suggested that the short-circuited droplet transfer can occur under the predominant influence of surface tension, while the model simulation results demonstrate the tendency for the transfer period to rise as the short circuit current clamp reduces and/or the grown droplet volume increases. Experimentally derived transfer characteristics validated the analytical transfer model as a development tool as illustrated in Chapter 4.

Adaptive techniques were developed and used to regulate and control the current clamping level during the welding process as a means of exploring the practical operating range of the alternate control technique. The conditional limits applied to the adaptive controller ensured that the experimental trials were performed in accordance with normal welding practices. The assessment of the control technique required the development of monitoring software, which differentiates the mechanisms of the weld spatter formation. The details of these techniques which take into account the current clamp level achieved, along with the differentiation and visual graduation of the weld spatter are discussed in Chapter 4.

The experimental trials proved conclusively that short-circuited droplet transfer can be realized under the predominant influence of surface tension, with the current clamp adaptively controlled to levels where the electromagnetic pinch force is insignificant.
Stable welding conditions were noted for Ar-23%CO₂ shielded welds for short circuit current clamping levels of 10-80A and mean short circuit transfer periods of 2.7-4.2ms. In contrast similar stable welding conditions were established with CO₂ shielded welds where current clamping levels of 145-200A were applied and where the stringent deadband of the adaptive controller ensured the mean short circuit transfer period did not exceed the 3.0ms upper boundary limit. It is anticipated that when this method of control is applied to welding applications using electrode wires and gases of different physical characteristics the approach taken when applying the alternative control technique may alter. Increased current clamp levels may be required to compensate for surface tension influences, which are reduced through the electrode or shielding gas composition. The arcing control parameters may also require revising to achieve the desired melting rate when using electrode wire of dissimilar resistivity.

The implementation of a short circuit current clamp resulted in significant improvements to the level of weld spatter. The results were comparable to control techniques using process specific power sources with premonition detection. An analysis of the graduated weld spatter and the stability index data indicated significant reductions in weld spatter were achieved when the current clamp level was maintained at or below 150A for Ar-23%CO₂ shielded and 200A for CO₂ shielded welds.

A further study was carried out to identify and assess optimum short circuit transfer conditions in dip transfer GMAW. The premise was that synchronizing the weld pool motion with the short-circuiting event is fundamental to weld stability and spatter reduction in dip transfer GMAW. As part of this work the electrode melting rate and the influence of anode and resistive heating was examined. Based on this study an analytical model of the electrode melting rate was developed with the aim of simulating the electrode melting rate behaviour for the alternative control waveform. The model’s algorithms were based principally on Halmoy’s work [102, 104, 106, 107]. These algorithms were verified by an analysis of the melting rate model and experimentally derived results for similar specified welding conditions as outlined in Chapter 5.

It was envisaged that arcing pulse parameters would have a significant impact on the electrode melting rate over a wide range of wire feed rates. Based on model simulation and later experimentally derived results a linear correlation between the arcing pulse
parameters and wire feed rate was identified where a stable welding condition and minimal spatter was attained. The relationship which is defined in Chapter 5 is expressed as \( a \times wfr + b = \sqrt{I^2_t \times T_p} \) with constants \( a \) & \( b \) dependent on shielding gas, electrode type and \( CTWD \).

The second stage in the assessment of optimum transfer conditions was a brief study of weld pool oscillation behaviour. Initially the correlation between the calculated and actual pool oscillation frequency was examined. Based on this work it was hypothesized that if the synchronized short-circuiting event occurred at an interval approximately 60\% into the weld pool oscillation cycle then an optimum short circuit transfer could be achieved with minimal current clamping. An analysis of the adaptively tuned current clamp levels of CO\(_2\) shielded welds and the hypothesized optimum short-circuiting condition would suggest a strong argument for this hypothesis as discussed in Section 5.3.5. In practice however the weld pool geometry will alter for a chosen parameter set as a direct result of variations in travel speed. From the work presented it could be concluded that optimization of the actual welding process is more likely achieved at higher dip frequencies where the short-circuiting event occurs within the initial half of the weld pool oscillation cycle.

During the process of evaluating and assessing the alternative control technique as a metal transfer control mechanism, various process irregularities during the short circuit and arcing period were identified. Investigations revealed some to be a direct result of implementing a current clamping methodology while the others were a feature of welding with a CO\(_2\) shielding gas. To minimize the impact of these irregularities various ancillary control strategies were developed and implemented to enhance the weld process stability. These are discussed in Section 4.5, with a more detailed study of the process irregularities presented in Sections 5.9 & 5.10.

The modelling and supporting experimental program has shown that the alternate control technique with its characteristic short circuit current clamping methodology can be utilized for the control of the dip transfer GMAW process. Therefore the control technique’s capacity to control heat input and fusion characteristics was examined.
Initial work briefly reviewed the effective heat input in dip transfer GMAW as outlined in Chapter 6.

The use of current as a control variable in dip transfer GMAW was examined. Three defined current formats: the average current, the average arcing current and the average cycle arcing current were evaluated for their correlation with heat input and impact on weld fusion characteristics. The investigation revealed that the weld fusion area and bead width have a strong linear correlation to calculated weldment heat input and the average cycle arcing current irrespective of the CTWD, while the average arcing current was noted to have the strongest correlation to the weld penetration depth. These results are found in Sections 6.6.1 & 6.6.2.

Finally the alternate control technique was assessed for its capacity to control heat input and fusion characteristics when exposed to variations in the welding torch orientation. An analysis of coated sheet steel welds demonstrated the superior capacity of the alternate control technique to produce consistent fusion characteristics, weld reinforcement and minimal coated surface damage irrespective of the coated material or welding torch orientation compared to constant voltage control techniques.

This research confirms that surface tension can be used as a predominant transfer mechanism in dip transfer GMAW. A short circuit current clamp can be implemented to significantly reduce the weld spatter generated. It was also shown that the synchronization of the short-circuiting event with the weld pool oscillation significantly influenced the minimum level of the current clamping. The alternative control technique has demonstrated the capacity to produce consistent weld penetration and fusion characteristics irrespective of variations in welding torch orientation or work-piece base material.

### 7.2 Conclusion

A novel current control approach has been developed for dip transfer GMAW, which provides de-coupled and independent control of the short circuit and arcing periods. It has been demonstrated that effective control of the dip transfer GMAW process can be achieved with conventional inverter power sources when using this novel control approach which utilizes a short circuit current clamp to limit the maximum current...
during the short circuit period. The arcing period is characterized by a droplet forming and arc heating phase.

A software configurable power source control system was developed and manufactured for this research. It was utilized in the development of novel control strategies for dip transfer GMAW. The developed control methodologies were executed in a real-time environment and applied to commercial inverter power sources.

The optimum short circuit current clamp levels have been determined experimentally using adaptive control techniques, which were developed and used in the control and regulation of the current clamp level. Significant reductions in spatter levels were achieved when the short circuit current was maintained at or below 150A with Ar-23%CO₂ shielded and 200A for CO₂ shielded welds.

A simple analytical model of the droplet transfer was developed which confirmed the feasibility of short circuit current clamping as a control methodology. The model demonstrated the impact on the short circuit transfer period as the current clamp level was lowered or the droplet volume increased. An electrode melting rate model was used to replicate the melting rate characteristics when using the alternative control technique. The model simulation results were later utilized in the identification and selection of optimum welding parameters for a range of wire feed rates.

It was found that the expression \( \sqrt{I_p^2 \times T_p} \) for the arcing pulse parameters was valid for a range of wire feed rates when using the same shielding gas, electrode and CTWD. This observation suggests significant setup time can be reduced once an initial optimum welding condition is identified.

An assessment of optimum short circuit transfer conditions has led to a hypothesis which proposes the optimum short circuit transfer is realized when the short-circuiting event occurs at an interval approximately 60% into the weld pool oscillation cycle. Support for this hypothesis comes from an analysis of current clamping levels, which were correlated with respect to the hypothesized event. Under such conditions minimum current clamp levels were noted.
In view of the random nature of the dip transfer welding process some additional ‘intelligent’ ancillary control to account for deviations from stable welding performance must be applied. Ancillary control strategies have been designed to address instabilities within the short circuit and arcing periods. This has lead to significant improvements in the stability of the welding process through the minimization of excessive short circuit and arcing periods, in particular when welding with a CO₂ shielding gas.

The initial investigations of weld fusion characteristics revealed the fusion area and bead width to have a strong linear correlation to the weldment heat input and average cycle arcing current irrespective of the CTWD, while the penetration depth is strongly dependent on the average arcing current. The alternative control technique demonstrated how consistent fusion characteristics, weld reinforcement and minimal coated surface damage was achieved irrespective of torch orientation or coated material when using a current control technique compared to the inconsistent results achieved when using a constant voltage technique.

The experimental program proved conclusively that the short-circuited droplet transfer in dip transfer GMAW can be realized under the predominant influence of surface tension with significant improvements to weld spatter achieved when the short circuit current is limited during the molten bridge rupture. The generated levels of spatter were comparable to other control techniques utilizing process specific power sources with short circuit rupture premonition detection. Ancillary control strategies are however required to maintain process stability.

7.3 Recommendation
In spite of the major achievements and findings of this thesis a number of unresolved issues still remain. These issues along with suggested recommendations for future research are as follows:

Even though this thesis has examined the alternative control technique as a control methodology for the dip transfer GMAW process, further research is still required to evaluate the control technique for welding applications using electrode wire gauges in excess of 0.9mm.
The majority of the welding trials reported have been carried out on mild steel base materials. Further work is required to ascertain the capabilities of the alternative control technique when welding other ferrous and non-ferrous base materials.

Before commercialisation of the control technique can be considered synergic control methodologies need to be examined and developed for the selection of suitable welding parameters over a range of welding applications.

Preliminary results of an investigation into extended arcing periods as discussed in Chapter 5 would suggest that high ripple frequency current flow produces more stable arc and droplet characteristics than that achieved with low ripple frequency current flow. Further research is required to ascertain the impact of the current ripple frequency on the arc and droplet stability in GMAW.

The average cycle arcing current is shown to have a strong correlation to heat input in dip transfer GMAW. It is envisaged that the development of this current format as an online control variable for heat input will offer significant benefits towards the regulation of weld fusion characteristics.
References


[34] Allum.C.J, & Quintino.L, ‘Control of fusion characteristics in pulsed current GMAW’, IIW Doc. 212-582-84.


Appendix 1
Test Rig Schematics

Figure A1.1. Test rig schematics – Cover page
<table>
<thead>
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<th>SHEET No.</th>
<th>DESCRIPTION</th>
<th>REV</th>
</tr>
</thead>
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<td>0</td>
</tr>
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<td>DRAWING INDEX</td>
<td>0</td>
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Figure A1.2. Test rig schematics – Index page
Figure A1.3. Test rig schematics – Isolation unit faceplate layout
Figure A1.4. Test rig schematics – Isolation unit board layout
Figure A1.5. Test rig schematics – Isolation unit control system layout
Figure A1.6. Test rig schematics – Reference isolation board power supplies
Figure A1.7. Test rig schematics – Reference isolation board
Figure A1.8. Test rig schematics – Voltage feedback isolation board
Figure A1.9. Test rig schematics – Current feedback isolation board
Figure A1.10. Test rig schematics – PC/32 Digital I/O board
Figure A1.11. Test rig schematics – Digital I/O & interrupt board
Figure A2.1. Hyspeed camera schematics – Cover page
Figure A2.2. Hyspeed camera schematics – Event & timing boards
Figure A2.3. Hyspeed camera schematics – Event & timing digital isolation
Appendix 4

Adaptive $V_{arc}$ Threshold Control Logic

A4.1 Voltage Filter

A digital recursive FIR filter is utilized to generate a filtered output from the welding voltage feedback. The currently sampled welding voltage and a recursive filtered voltage component from the previous scan are applied to the algorithm as weighted values based on the coefficients $\alpha_1$ & $\alpha_2$ (the coefficient values determine the degree of filtering).

$$V_{weld\_filter} = \alpha_1 \times V_{weld\_fb} + \alpha_2 \times Last\_V_{weld\_filter}$$

$$Last\_V_{weld\_filter} = V_{weld\_filter}$$

A4.2 Adaptive $V_{arc}$ Threshold Control

The control logic modifies the $V_{arc}$ threshold level when the current clamp is released and the current rises towards the current limit $I_{sc\_lim}$ setpoint. The primary function of the control is to compensate for the increased IR voltage drop that accompanies the increased current.

```scheme
if (Current Clamp Logic = Disabled)
{
If the short circuit current clamp is disabled and the welding current is less than the current limit setpoint. Then calculated the adaptive $V_{arc}$ threshold.

```scheme
if (I_{weld\_fb} < I_{sc\_lim})
{
Determine the minimum short circuit resistance $R_{sc\_min}$ once the current clamp logic is disabled and the current is increased towards the $I_{sc\_lim}$ setpoint.

$$R_{sc} = V_{weld\_fb} / I_{weld\_fb}$$

if ($R_{sc} < R_{sc\_min}$)
$$R_{sc\_min} = R_{sc}$$

Estimate the instantaneous short circuit voltage from the minimum short circuit resistance $R_{sc\_min}$ to minimize the influence of an increasing bridge resistance as the molten bridge necks. If current limit $I_{sc\_lim}$ is reached, hold the estimated value of short circuit voltage $V_{est}$.

$$V_{est} = I_{weld\_fb} \times R_{sc\_min}$$
```
Appendix 3
Investigation of Extended Arcing Periods

A3.1 Captured Events Low Frequency Current Ripple Analysis

The following is a summary of the investigation into extended arcing periods described in Chapter 5, based on captured photographic images and transient waveforms. The power source background current ripple frequency is 300Hz.

Table A3.1. Extended Arcing Analysis - Low Frequency Current Ripple

<table>
<thead>
<tr>
<th>No.</th>
<th>$I_{pk}/I_{bkd}$ A / ms / A</th>
<th>$T_{arc-lim}$ ms</th>
<th>$T_{det-sc}$ ms</th>
<th>Summary of Analysis</th>
</tr>
</thead>
</table>
| 1   | 230/1.5/50              | 40              | 15              | a) Droplet repulsed during S/C. 
                                |                |                 | b) Large non-axisymmetric droplet growth. |
| 2   | 225/1.5/60              | 40              | 15              | a) Droplet repulsed during previous S/C. Sporadic arc and droplet motion. 
                                |                |                 | b) Large non-axisymmetric droplet growth. |
| 3   | 225/1.35/70             | 40              | 10              | a) Sporadic arc and droplet motion. 
                                |                |                 | b) Large non-axisymmetric droplet growth. |
| 4   | 225/1.5/60              | 40              | 10              | a) Sporadic arc and droplet motion. 
                                |                |                 | b) Large non-axisymmetric droplet growth. |
| 5   | 225/1.5/60              | 40              | 63              | a) Arc and droplet motion during arcing pulse. 
                                |                |                 | b) Large arc length at image capture. Excessive droplet motion after the detected event. |
| 6   | 225/1.5/60              | 40              | 32              | a) Incipient short after arc pulse, droplet repulsed. 
                                |                |                 | b) Large non-axisymmetric growth. (Fig.5-23) |
| 7   | 225/1.5/60              | 40              | 25              | a) No identified irregularity. 
                                |                |                 | b) Non-axisymmetric droplet growth. |
| 8   | 230/1.5/50              | 30              | 17              | a) Droplet repulsed during S/C wetting-in. 
                                |                |                 | b) Large non-axisymmetric droplet growth. |
| 9   | 220/1.5/60              | 40              | 1               | a) Sporadic arc and droplet motion. 
                                |                |                 | b) Large non-axisymmetric droplet growth. |
| 10  | 220/1.5/60              | 40              | 30              | a) Droplet repulsed during S/C wetting-in. 
                                |                |                 | b) Large non-axisymmetric growth. (Fig.5.21) |
| 11  | 220/1.5/60              | 40              | 1               | a) Sporadic arc and droplet motion. 
                                |                |                 | b) Large non-axisymmetric droplet growth. |
| 12  | 250/1.5/40              | 30              | 4               | a) Sporadic arc and droplet motion during arc pulse. 
                                |                |                 | b) Large droplet growth on side-wall of electrode. |
| 13  | 210/1.5/60              | 30              | 1               | a) Droplet repulsed during previous S/C wetting-in. 
                                |                |                 | b) Non-axisymmetric droplet growth. |
| 14  | 220/1.5/55              | 40              | 13              | a) Droplet repulsed during previous S/C. Sporadic arc and droplet motion during arc pulse. 
                                |                |                 | b) Non-axisymmetric droplet growth. |

Table legend: $T_{arc-lim}$ - Arcing period threshold detection limit, $T_{det-sc}$ - Delay interval between detection and short-circuiting event.
Figure A3.1. Image and transient waveform of extended arcing event 1

Figure A3.2. Image and transient waveform of extended arcing event 2
Figure A3.3. Image and transient waveform of extended arcing event 3

Figure A3.4. Image and transient waveform of extended arcing event 4
Figure A3.5. Image and transient waveform of extended arcing event 5

Figure A3.6. Image and transient waveform of extended arcing event 7
Figure A3.7. Image and transient waveform of extended arcing event 8

Figure A3.8. Image and transient waveform of extended arcing event 9
Figure A3.9. Image and transient waveform of extended arcing event 11

Figure A3.10. Image and transient waveform of extended arcing event 12
(a) Captured image of extended arcing condition

(b) Pre-triggered conditions

(c) Triggered event

Figure A3.11. Image and transient waveform of extended arcing event 13

(a) Captured image of extended arcing condition

(b) Pre-triggered conditions

(c) Triggered event

Figure A3.12. Image and transient waveform of extended arcing event 14
A3.2 Captured Events High Frequency Current Ripple Analysis

The following is a summary of the investigation into extended arcing periods described in Chapter 5, based on captured photographic images and transient waveforms. The power source background current ripple frequency is 4kHz.

Table A3.2. Extended Arcing Analysis - High Frequency Current Ripple

<table>
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<th>No.</th>
<th>I_{pk}/T_{arc}/I_{bkd}</th>
<th>T_{arc-lim} ms</th>
<th>T_{det-sc} ms</th>
<th>Summary of Analysis</th>
</tr>
</thead>
</table>
| 15  | 220/60/1.5            | 20             | 7-8          | a) Droplet repulsed during previous S/C.  
                                          b) Non-axisymmetric droplet growth. |
| 16  | 230/50/1.5            | 20             | 3-4          | a) Sporadic arc and droplet motion.  
                                          b) Non-axisymmetric droplet growth. |
| 17  | 230/50/1.5            | 30             | 3            | a) Droplet repulsed during S/C. Incipient S/C during arc pulse. Arc and droplet motion.  
                                          (Fig.5.20)  
                                          b) Large droplet growth on the electrode side-wall. |
| 18  | 220/60/1.5            | 40             | 7            | a) Droplet repulsed during S/C. Arc root and droplet motion.  
                                          b) Large non-axisymmetric droplet growth. |
| 19  | 220/60/1.5            | 40             | 6            | a) Sporadic arc and droplet motion.  
                                          b) Large non-axisymmetric growth.  
                                          (Fig.5.24) |
| 20  | 230/50/1.5            | 30             | 20           | a) No identified irregularity.  
                                          b) Large non-axisymmetric droplet growth. |
| 21  | 230/50/1.5            | 30             | 3            | a) No identified irregularity.  
                                          b) Non-axisymmetric droplet growth |
| 22  | 250/40/1.5            | 20             | 2            | a) Sporadic arc and droplet motion.  
                                          b) Non-axisymmetric droplet growth. |
(a) Captured image of extended arcing condition

(b) Pre-triggered conditions

(c) Triggered event

Figure A3.13. Image and transient waveform of extended arcing event 15

(a) Captured image of extended arcing condition

(b) Pre-triggered conditions

(c) Triggered event

Figure A3.14. Image and transient waveform of extended arcing event 16
Figure A3.15. Image and transient waveform of extended arcing event 18

Figure A3.16. Image and transient waveform of extended arcing event 20
Figure A3.17. Image and transient waveform of extended arcing event 21

Figure A3.18. Image and transient waveform of extended arcing event 22
Appendix 4

Adaptive $V_{\text{arc}}$ Threshold Control Logic

A4.1 Voltage Filter

A digital recursive FIR filter is utilized to generate a filtered output from the welding voltage feedback. The currently sampled welding voltage and a recursive filtered voltage component from the previous scan are applied to the algorithm as weighted values based on the coefficients $\alpha_1 \& \alpha_2$ (the coefficient values determine the degree of filtering).

$$V_{\text{weld\_filter}} = \alpha_1 \times V_{\text{weld\_fb}} + \alpha_2 \times \text{Last}_V_{\text{weld\_filter}}$$

$$\text{Last}_V_{\text{weld\_filter}} = V_{\text{weld\_filter}}$$

A4.2 Adaptive $V_{\text{arc}}$ Threshold Control

The control logic modifies the $V_{\text{arc}}$ threshold level when the current clamp is released and the current rises towards the current limit $I_{\text{sc\_lim}}$ setpoint. The primary function of the control is to compensate for the increased IR voltage drop that accompanies the increased current.

```plaintext
if (Current Clamp Logic = Disabled)
{
If the short circuit current clamp is disabled and the welding current is less than the current limit setpoint. Then calculated the adaptive $V_{\text{arc}}$ threshold.

```plaintext
```plaintext
if (I_{\text{weld\_fb}} < I_{\text{sc\_lim}})
{
```plaintext
```plaintext
Determine the minimum short circuit resistance $R_{\text{sc\_min}}$ once the current clamp logic is disabled and the current is increased towards the $I_{\text{sc\_lim}}$ setpoint.

$$R_{\text{sc}} = \frac{V_{\text{weld\_fb}}}{I_{\text{weld\_fb}}}$$

if ($R_{\text{sc}} < R_{\text{sc\_min}}$)

```

$$R_{\text{sc\_min}} = R_{\text{sc}}$$

Estimate the instantaneous short circuit voltage from the minimum short circuit resistance $R_{\text{sc\_min}}$ to minimize the influence of an increasing bridge resistance as the molten bridge necks. If current limit $I_{\text{sc\_lim}}$ is reached, hold the estimated value of short circuit voltage $V_{\text{est}}$.

$$V_{\text{est}} = I_{\text{weld\_fb}} \times R_{\text{sc\_min}}$$

```plaintext
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```plaintext
if ($I_{\text{weld fb}} \geq I_{\text{sc lim}}$)
{
    Once the $I_{\text{sc lim}}$ is reached the voltage feedback may continue to slowly rise due to the gradual necking of the molten bridge under current limit conditions. An estimate of the necking voltage during the current limit is derived from the difference of the filtered voltage feedback $V_{\text{weld filter}}$ which tracks the short circuit voltage and the estimated short circuit voltage $V_{\text{est}}$.
    
    $V_{\text{neck}} = V_{\text{weld filter}} - V_{\text{est}}$
}

The $V_{\text{arc}}$ threshold level is calculated from the sum of the estimated short circuit and necking voltage.

$$V_{\text{arc thres}} = V_{\text{est}} + V_{\text{neck}} + \text{offset};$$

else

If the short circuit current clamp is enabled set the $V_{\text{arc}}$ threshold level to the setpoint value.

$$V_{\text{arc thres}} = V_{\text{arc thres sp}}$$
}

A4.3 Arc Detection

The re-established arc is detected if the voltage feedback is greater than the $V_{\text{arc}}$ threshold level.

if $V_{\text{weld fb}} > V_{\text{arc thres}}$