Liquid Metal Oscillation and Arc Behaviour during Welding
The research described in this thesis was performed in the department of Materials Science and Technology, Delft University of Technology, Mekelweg 2, 2628CD Delft, The Netherlands.

Front cover: Stereogram of metal transfer during gas metal arc welding by B.Y.B. Yudodibroto.
Liquid Metal Oscillation and Arc Behaviour during Welding

Proefschrift

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door

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<th>Description</th>
<th>Units</th>
</tr>
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<tbody>
<tr>
<td>$A$</td>
<td>weld area</td>
<td>mm$^2$</td>
</tr>
<tr>
<td>$A_d$</td>
<td>area of the pendant droplet cross-section</td>
<td>mm$^2$</td>
</tr>
<tr>
<td>$A_w$</td>
<td>area of the wire cross-section</td>
<td>mm$^2$</td>
</tr>
<tr>
<td>$D$</td>
<td>diameter</td>
<td>mm</td>
</tr>
<tr>
<td>$D_{eq}$</td>
<td>equivalent diameter</td>
<td>mm</td>
</tr>
<tr>
<td>$D_b$</td>
<td>weld pool bottom diameter</td>
<td>mm</td>
</tr>
<tr>
<td>$D_t$</td>
<td>weld pool top diameter</td>
<td>mm</td>
</tr>
<tr>
<td>$d\gamma/dT$</td>
<td>temperature coefficient of the surface tension</td>
<td>N m$^{-1}$ K$^{-1}$</td>
</tr>
<tr>
<td>$\Delta f$</td>
<td>frequency resolution</td>
<td>Hz</td>
</tr>
<tr>
<td>$\Delta x$</td>
<td>eccentricity of the arc with respect to the weld pool</td>
<td>mm</td>
</tr>
<tr>
<td>$e$</td>
<td>weld eccentricity</td>
<td></td>
</tr>
<tr>
<td>$E$</td>
<td>electric field strength</td>
<td>V mm$^{-1}$</td>
</tr>
<tr>
<td>$E_{ba}$</td>
<td>electric field strength at the bright arc region</td>
<td>V mm$^{-1}$</td>
</tr>
<tr>
<td>$E_{na}$</td>
<td>electric field strength at the normal arc region</td>
<td>V mm$^{-1}$</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>emission coefficient of the plasma</td>
<td>W m$^{-3}$</td>
</tr>
<tr>
<td>$f$</td>
<td>oscillation frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$f_p$</td>
<td>pulse frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$f_{ref}$</td>
<td>reference frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$f_t$</td>
<td>trigger frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$F_{arc}$</td>
<td>arc force</td>
<td>N</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>surface tension</td>
<td>N m$^{-1}$</td>
</tr>
<tr>
<td>$h$</td>
<td>equivalent weld pool depth</td>
<td>mm</td>
</tr>
<tr>
<td>$h$</td>
<td>weld pool height</td>
<td>mm</td>
</tr>
<tr>
<td>$H$</td>
<td>weld pool depth</td>
<td>mm</td>
</tr>
<tr>
<td>$I$</td>
<td>welding current</td>
<td>A</td>
</tr>
<tr>
<td>$I_b$</td>
<td>welding base current</td>
<td>A</td>
</tr>
<tr>
<td>$I_p$</td>
<td>welding pulse current</td>
<td>A</td>
</tr>
<tr>
<td>$I_t$</td>
<td>welding trigger current</td>
<td>A</td>
</tr>
<tr>
<td>$J$</td>
<td>current density</td>
<td>A mm$^{-2}$</td>
</tr>
<tr>
<td>$k$</td>
<td>wave number</td>
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<tr>
<td>$l_{arc}$</td>
<td>arc length</td>
<td>mm</td>
</tr>
<tr>
<td>$l_{ba}$</td>
<td>length of the bright arc region</td>
<td>mm</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Units</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>$l_d$</td>
<td>length of the pendant droplet</td>
<td>mm</td>
</tr>
<tr>
<td>$l_{na}$</td>
<td>length of the normal arc region</td>
<td>mm</td>
</tr>
<tr>
<td>$l_w$</td>
<td>length of the solid wire</td>
<td>mm</td>
</tr>
<tr>
<td>$L_b$</td>
<td>weld pool bottom length</td>
<td>mm</td>
</tr>
<tr>
<td>$L_t$</td>
<td>weld pool top length</td>
<td>mm</td>
</tr>
<tr>
<td>$\lambda_{crit}$</td>
<td>critical wavelength</td>
<td>mm</td>
</tr>
<tr>
<td>$m$</td>
<td>mass</td>
<td>kg</td>
</tr>
<tr>
<td>$n$</td>
<td>number of data</td>
<td></td>
</tr>
<tr>
<td>$N_0$</td>
<td>eigenvalue for the lowest oscillation mode</td>
<td></td>
</tr>
<tr>
<td>$N_1$</td>
<td>eigenvalue for the second lowest oscillation mode</td>
<td></td>
</tr>
<tr>
<td>$P_{arc}$</td>
<td>arc pressure</td>
<td>MPa</td>
</tr>
<tr>
<td>$p$</td>
<td>pressure</td>
<td>atm</td>
</tr>
<tr>
<td>$R$</td>
<td>arc radius</td>
<td>mm</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density</td>
<td>kg m$^{-3}$</td>
</tr>
<tr>
<td>$\rho_d$</td>
<td>resistivity of the pendant droplet</td>
<td>m$\Omega$ mm</td>
</tr>
<tr>
<td>$\rho_w$</td>
<td>resistivity of the solid wire</td>
<td>m$\Omega$ mm</td>
</tr>
<tr>
<td>$S$</td>
<td>sampling rate</td>
<td>sample s$^{-1}$</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
<td>s</td>
</tr>
<tr>
<td>$t_b$</td>
<td>base time</td>
<td>ms</td>
</tr>
<tr>
<td>$t_p$</td>
<td>pulse time</td>
<td>ms</td>
</tr>
<tr>
<td>$t_t$</td>
<td>trigger time</td>
<td>ms</td>
</tr>
<tr>
<td>$t_{weld}$</td>
<td>welding time</td>
<td>s</td>
</tr>
<tr>
<td>$U$</td>
<td>voltage</td>
<td>V</td>
</tr>
<tr>
<td>$U_{an}$</td>
<td>voltage over the anode fall region</td>
<td>V</td>
</tr>
<tr>
<td>$U_{arc}$</td>
<td>arc voltage</td>
<td>V</td>
</tr>
<tr>
<td>$U_{ba}$</td>
<td>voltage over the bright arc region</td>
<td>V</td>
</tr>
<tr>
<td>$U_{cat}$</td>
<td>voltage over the cathode fall region</td>
<td>V</td>
</tr>
<tr>
<td>$U_{col}$</td>
<td>voltage over the arc column</td>
<td>V</td>
</tr>
<tr>
<td>$U_d$</td>
<td>voltage along the liquid droplet</td>
<td>V</td>
</tr>
<tr>
<td>$U_{na}$</td>
<td>voltage over the normal arc region</td>
<td>V</td>
</tr>
<tr>
<td>$U_{ref}$</td>
<td>reference voltage</td>
<td>V</td>
</tr>
<tr>
<td>$U_w$</td>
<td>voltage along the electrode extension</td>
<td>V</td>
</tr>
<tr>
<td>$v$</td>
<td>welding travel speed</td>
<td>mm s$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>wave speed</td>
<td>mm s$^{-1}$</td>
</tr>
<tr>
<td>$V$</td>
<td>volume</td>
<td>mm$^3$</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Units</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>$W$</td>
<td>weld pool width</td>
<td>mm</td>
</tr>
<tr>
<td>$W_b$</td>
<td>weld pool bottom width</td>
<td>mm</td>
</tr>
<tr>
<td>$WFR$</td>
<td>wire feed rate</td>
<td>mm s$^{-1}$</td>
</tr>
<tr>
<td>$W_t$</td>
<td>weld pool top width</td>
<td>mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constant</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g$</td>
<td>acceleration due to gravity</td>
<td>9.8 m s$^{-2}$</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>magnetic permeability of free space</td>
<td>$4\pi \times 10^{-7}$ Wb A$^{-1}$ m$^{-1}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
</tr>
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<tbody>
<tr>
<td>GMA</td>
<td>Gas Metal Arc</td>
</tr>
<tr>
<td>GTA</td>
<td>Gas Tungsten Arc</td>
</tr>
<tr>
<td>P-GMA</td>
<td>Pulsed-current Gas Metal Arc</td>
</tr>
<tr>
<td>P-GTA</td>
<td>Pulsed-current Gas Tungsten Arc</td>
</tr>
<tr>
<td>S-GMA</td>
<td>Short-circuiting Gas Metal Arc</td>
</tr>
</tbody>
</table>
Chapter 1
General introduction

1.1 Background

Of the various welding processes used in industry, those involving arc welding are widely employed for the joining of metals. The main reason for this is that the heat to melt the workpiece or the metals to be joined can be generated and controlled easily in a relatively inexpensive way. The source of this heat is an electric arc, which is created between a welding electrode and a workpiece, both of which are connected to a suitable source of electrical power (figure 1.1). Since the first use of arc welding in the 1880s, a number of variants have been developed.\cite{1,2} Among these are gas tungsten arc (GTA) welding and gas metal arc (GMA) welding. In GTA welding the electrode is non consumable whereas in GMA welding the electrode is melted, transferred to the weld pool and becomes part of the weld. While GTA welding is largely used in applications where weld quality is of greater importance than welding speed, GMA welding has gained popularity due to its high deposition rate and high travel speed.

Figure 1.1 Principle of the heat generation in arc welding
Variation of weld penetration during arc welding is one of the most important problems that influence weld quality. Different states of weld penetration are schematically presented in figure 1.2. Incomplete or partially penetrated welds can considerably reduce the strength and the corrosion resistance of welded structures. Over-penetration can also lead to the same problems and, eventually, can end up as burn-through. This penetration inconsistency can be caused by a variety of factors such as the variation in material thickness, the chemical composition of the material or of the welding process. Even though the variation of the weld penetration can be reworked or repaired, such procedures can be time consuming and expensive.

Figure 1.2  Variation of weld penetration during welding.

An example of expensive welding rework can be found in the offshore pipeline construction industry where multi-pass welding is carried out on pipe-laying vessels. To join the pipe, the pipe ends need to be bevelled (prepared by machining them to a certain angle and geometry dependent on the required welding groove) and then aligned. Afterwards, welding is performed to produce the root pass, followed by the hot pass, the fill passes and finally the cap. Partial or lack of penetration may occur on the weld root (figure 1.3). When this is detected during non-destructive inspection, the weld need to be cut and the whole process has to be repeated which, dependent on the pipe size, can take up to a few hours. With a vessel operation cost in the order of several hundred thousand euro per day, the occurrence of lack of penetration can significantly increase the total production cost.

Variation of weld penetration can be prevented using an adequate current level in combination with a backing system (figure 1.4). The adequate current level assures the formation of complete joint penetration. The backing material supports the molten weld metal to prevent burn-through. This approach,
however, cannot be used when there is limited or no access to the back (root) of the metal to be joined, for instance during the welding of small diameter tubes or pipe-in-pipe constructions.

Figure 1.3 Lack of penetration in multi-pass welding. The dashed line indicates the welding groove.

Figure 1.4 Schematic presentation of a weld backing system before (left) and after welding (right).

Another way to prevent the variation of weld penetration is by monitoring the welding conditions continuously and adjusting the welding parameters if some unwanted variations occur. In manual welding this is a daily task of the welders. They use their eyes, ears, and skill to interpret the welding conditions and if required adjust the welding parameters to obtain the desired conditions. In automated welding, depending on the degree of the automation, the task of the welder is taken over by the welding equipment. Monitoring of the welding conditions, including the detection of weld imperfections, is realized by sensors. With increasing use of automated welding process in industry nowadays, the role of welding sensors has become more and more important. A number of penetration sensing systems have been developed based on different techniques, as presented in table 1.1.
Table 1.1  Various techniques for weld penetration sensing.[3-7]

<table>
<thead>
<tr>
<th>Sensing technique</th>
<th>Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitoring the temperature around the weld pool</td>
<td>Thermocouples, Infra-red camera</td>
</tr>
<tr>
<td>Monitoring ultrasonic or acoustic emission signals</td>
<td>Ultrasonic transducer, Acoustic emission transducer</td>
</tr>
<tr>
<td>Determination of the onset of weld pool sag</td>
<td>Arc (voltage) sensor, Laser sensor</td>
</tr>
<tr>
<td>Monitoring the weld pool size</td>
<td>Photodiode array, CCD (charged coupled device) camera</td>
</tr>
<tr>
<td>Trace element monitoring</td>
<td>Spectrometer</td>
</tr>
<tr>
<td>Measurement of the weld pool oscillation frequency</td>
<td>Arc (voltage) sensor, Light sensor</td>
</tr>
</tbody>
</table>

Of the various techniques mentioned in table 1.1, penetration sensing based on weld pool oscillation has the advantage that it can be used for all positional welding and the arc itself can be used as the sensor without the need of additional complex equipment. This penetration sensing technique is based on the oscillation behaviour of the weld pool. When the weld pool is excited by an external force, for instance due to a sudden increase of arc pressure, it starts to oscillate (figure 1.5). The mode of oscillation is dependent on the state of the weld penetration. A partially penetrated weld pool oscillates with a higher frequency in comparison to a fully penetrated pool. This frequency can be determined from the voltage signals as these signals are related to the arc length.

Figure 1.5  Weld pool oscillations in partial and full penetration conditions.
Since the 1980s, extensive studies of weld pool oscillation and its application for weld penetration sensing have been carried out. At Delft University of Technology, research on this subject was initially focussed on the fundamentals of the weld pool oscillation phenomenon during GTA welding. Further research has resulted in the development of a patented weld penetration sensing and control system for pulsed-current GTA (P-GTA) welding. The possibilities of using the weld pool oscillation behaviour for penetration sensing in the case that a weld pool is elongated has also been investigated.

GMA welding offers a higher deposition rate and travel speed than GTA welding. The possibility to use a penetration sensing system during GMA welding will be very beneficial to increase productivity. As far as oscillation based penetration sensing is concerned, the use of such a technique in GMA welding to date has not been successful. In comparison to GTA, the GMA welding process is much more complex, as it makes use of a consumable electrode. During welding this electrode will melt and transfer to the weld pool. The formation of the liquid drop at the electrode tip as well as the transfer of this droplet to the weld pool can influence the arc behaviour. It is evident that for the use of a penetration sensor based on pool oscillation in GMA welding, more understanding on the weld pool dynamics and the influence of the metal transfer on the arc behaviour is required.

1.2 Research goal

The goal of this research is to obtain insight into the oscillation behaviour of the liquid metal, i.e. the weld pool and the pendant droplet, and the arc behaviour during GMA welding. To achieve this goal, the work was performed in two stages.

Firstly, research on GTA welding with a cold-wire addition is described. In this process the filler wire is introduced into the weld pool without preheating. Since the filler wire is not part of the electrical circuit, the metal transfer has a less disturbing effect on the electrical signals than in the case of GMA welding. Of the few earlier investigations on weld pool oscillation during cold-wire GTA, it was reported that metal transfer reduces the accuracy of the determination of oscillation frequency from the voltage signals. However, the exact mechanism behind this phenomenon was not well understood. This issue was dealt with in the first stage of the current research. Different transfer modes, namely uninterrupted bridging transfer, where the liquid metal flows smoothly into the pool, and interrupted bridging transfer, where the filler wire
regularly contacts the weld pool, were considered. The influence of the wire addition on the weld pool oscillatory behaviour and on the voltage signals has also been studied. In addition, the possibility to use weld pool oscillation for penetration sensing and control during cold-wire GTA welding is explored.

In the second stage, the focus turned to GMA welding where the filler wire is part of the electrical circuit. Research on weld pool oscillation during GMA welding in the past was carried out using short-circuiting GMA welding (S-GMA welding). With this process, monitoring of weld pool oscillation is difficult due to regular contact between the electrode and the weld pool, which disturbs the pool oscillation and the voltage. Pulsed-current GMA (P-GMA) welding was selected for the current research, since the process can be operated free of short-circuits. In P-GMA welding, the welding current is switched periodically between a low base current and a high pulse current. Metal transfer can be controlled in such a way that a droplet is detached every pulse. The time interval between pulses, during which monitoring of the weld pool oscillation is carried out, can be adjusted over a wide range. The underlying questions posed in the second stage of this research concern:

- The current pulse and the metal transfer effects on the weld pool dynamics in P-GMA welding.
- Features of the dynamic behaviour of the pendant droplet and the weld pool during P-GMA welding.
- The effect of the pendant droplet on the arc behaviour.
- The influence of arc behaviour on arc voltage.
- Monitoring of weld pool oscillations in P-GMAW using voltage signal measurements and the suitability for penetration control.

To address these questions:

- The wire feed rate is de-coupled from other welding parameters as far as possible.
- The oscillation behaviour of the weld pool and the droplet is examined using high-speed imaging techniques and electrical signal measurements.
- The behaviour of the arc structure based on the intensity of the arc is considered.
- A new approach to relate the arc length and the arc voltage, identifying the existence of different arc regions is assessed.
1.3 Thesis outline

The outline of the thesis is as follows. In chapter 2, the principles of arc welding and weld pool oscillation are described. An overview of mathematical models describing the oscillation of the weld pool is also given. Chapter 3 deals with experimental work on liquid metal oscillation during cold-wire GTA welding. The study concerns uninterrupted and interrupted metal transfer modes. The frequency of pool oscillation is determined using both a high-speed imaging technique and measurement of voltage signals. Information on the influence of the wire addition on the oscillatory behaviour of the weld pool is also presented. In chapter 4, the possibilities and the limitations of using the weld pool oscillation behaviour for penetration sensing and control during cold-wire GTA welding are described. Chapter 5 deals with liquid metal and arc behaviour during P-GMA welding. In this chapter, the results of experimental work to characterise weld pool oscillations during P-GMA welding of mild steel is presented. Attempts to monitor the frequency of the weld pool oscillation by means of high-speed imaging and from the electric signals are described. The relationship between the arc length and the arc voltage is discussed. An approach to clarify the irregularity of the voltage due to the alteration of the arc structure is also suggested. Finally, general discussion and conclusions from this research are given in chapter 6.
References


Chapter 2:
Background

In this chapter, the principles of arc welding and liquid metal oscillation during arc welding are described. The basics of gas tungsten arc (GTA) welding and gas metal arc (GMA) welding are given in section 2.1. The principles of the weld pool oscillation phenomena are presented in section 2.2. An overview of the analytical and the numerical models describing the phenomena is given in the same section. In section 2.3 the pendant and the free droplet oscillation phenomena are described.

2.1 Arc welding

2.1.1 Gas tungsten arc welding

In GTA welding the arc is created between a non consumable electrode and the workpiece. The electrode consists of tungsten to withstand very high temperatures with minimal erosion. The electrode may contain a small amount of oxide (such as those of zirconium, thorium, lanthanum, yttrium or cerium) to stabilise the arc and to improve the electron emission characteristics. The electrode and the molten metal are protected from oxidation by supplying a shielding gas to the arc zone. Commonly an inert gas such as argon, helium or a mixture of both is used. Hydrogen can be added to shielding gases for GTA welding of austenitic stainless steels to reduce oxide formation and to increase penetration. GTA welding can be performed without filler wire (autogenous GTA welding) or with addition of filler wire, depending on the requirements. In practice, filler wire is used to fill a gap or to change the chemical composition of the weld in order to improve the corrosion resistance or the mechanical properties. When filler metal is required, it can be introduced to the weld pool without preheating (cold-wire GTA welding) or in a hot condition in which the wire is brought to a higher temperature by means of resistance heating (hot-wire
GTA welding) to obtain a higher deposition rate.\cite{1} The arrangement of GTA welding is illustrated in figure 2.1.

Figure 2.1  Schematic presentation of GTA welding.

Preliminary experiments with cold-wire GTA welding showed that when the filler wire is fed continuously, the delivery position dictates the way the metal is transferred from the filler wire to the weld pool. When the wire delivery position is too low (figure 2.2a), the tip of the wire strikes the workpiece in front of the weld pool. This situation may result in intermittent wire melting. At a higher wire delivery position uninterrupted bridging transfer takes place (figure 2.2b). The liquid metal flows smoothly at the leading edge of the pool and virtually no agitation of the weld pool is observed. This is the ideal situation for welding under normal conditions. When the wire delivery position is raised further, a continuously growing droplet is formed at the wire tip. Metal transfer takes place when the growing droplet touches the weld pool, which results in interrupted bridging transfer (figure 2.2c). At an even higher wire delivery position, free flight droplet transfer may occur, during which the droplet grows to a considerable size and then detaches, mainly due to gravity (figure 2.2d).

Figure 2.2  Schematic illustration of metal transfer modes during cold-wire GTA welding, a) intermittent wire melting, b) uninterrupted bridging transfer, c) interrupted bridging transfer and d) free flight transfer.
2.1.2 Gas metal arc welding

In GMA welding the arc is established between the workpiece and a consumable wire electrode. As in GTA welding, the arc and the molten metal in the weld pool are protected from the environment by a shielding gas. A wide range of shielding gases is available. Beside the use of a single gas, such as Ar, He or CO₂, mixtures of two, three or more gases can also be used to improve the weld quality and process stability. [1,2] A schematic diagram of GMA welding is presented in figure 2.3.

![Schematic presentation of GMA welding.](image)

Figure 2.3  Schematic presentation of GMA welding.

An essential feature of GMA welding is the growth and the subsequent detachment of the liquid droplets at the electrode tip. This feature is strongly influenced by welding conditions, most importantly by the welding current. In the case of a low current and a short arc, metal transfer can take place in a short-circuiting transfer mode (figure 2.4a). This short-circuiting GMA welding (S-GMA welding) is characterised by the occurrence of regular contact between the electrode and the weld pool, during which the arc is extinguished and a liquid bridge is formed between the electrode and the weld pool. When the liquid bridge ruptures, metal transfer takes place and the arc is re-ignited. These features reduce the heat input and, therefore, permit all-positional welding and joining of thin materials in which thermal distortion is a concern. At a low welding current and with a relatively long arc a globular transfer mode occurs during which a large molten droplet is formed, which is detached mainly by gravity (figure 2.4b). When the welding current increases and exceeds a certain limit, a spray transfer mode is produced where very small droplets are formed, detached and accelerated axially across the arc (figure 2.4c). The current at which this transition occurs is known as the spray transition current. Since the spray transfer mode only occurs at relatively high currents, the heat input is high.
and the weld pool is large. The positional capabilities of the spray transfer operating mode are limited, but this mode offers a high deposition rate.

![Figure 2.4 Schematic illustration of a) short-circuiting, b) globular and c) spray transfers during GMA welding.](image)

Another variant of GMA welding is pulsed-current GMA welding (P-GMA welding). In this process the welding current is switched periodically between a low base current and a high pulse current (higher than the spray transition current). The low base current is used to maintain the arc, whereas the peak current is used to melt and detach the droplet as well as to melt the workpiece; as a result, stable spray transfer can be established while the mean current and thus the heat input is kept low.

### 2.1.3 Welding arc

The heat source used to melt the metal in arc welding is the electric arc. Lancaster defined an arc as an electrical discharge between electrodes in a gas or vapour environment. The arc created between the welding electrode and the workpiece can be subdivided into three main parts: the cathode fall region, the arc column and the anode fall region. The electrode may act as the cathode or the anode dependent on its polarity. In the case of GTA welding the tungsten electrode commonly acts as the cathode whilst in the case of GMA welding the wire electrode usually acts as the anode, as shown in figure 2.5. The anode and the cathode fall regions consist of a thin layer with a thickness in the range of $10^{-5}$ m to $10^{-6}$ m.
The arc voltage $U_{\text{arc}}$ consists of the voltage drops over the anode fall region $U_{\text{an}}$, over the arc column $U_{\text{col}}$ and over the cathode fall region $U_{\text{cat}}$ as expressed by:[5,6]

$$U_{\text{arc}} = U_{\text{an}} + U_{\text{col}} + U_{\text{cat}}.$$ \hspace{1cm} (2.1)

In practice, measurement of arc voltage during welding includes also the voltage drop over the electrode. In the case of GTA welding this is usually considered to be constant. In the case of GMA welding the melting and the detachment of the droplet from the filler wire will change the arc length and the wire length. These changes will influence the total voltage and, therefore, need to be taken into account. An expression for the voltage in GMA welding is given by:[7]

$$U_{AB} = U_{w} + U_{d} + U_{\text{an}} + U_{\text{col}} + U_{\text{cat}}.$$ \hspace{1cm} (2.2)

The total voltage $U_{AB}$ consists of the voltage drop along the wire/electrode extension $U_{w}$, the voltage drop at the droplet $U_{d}$, the voltage drop in the anode region $U_{an}$, the voltage drop in the arc column $U_{col}$ and the voltage drop in the cathode region $U_{cat}$.
While $U_{an}$ and $U_{cat}$ are virtually independent of the arc length, $U_{col}$ increases with the arc length $l_{arc}$ and the electric field strength $E$ in the plasma as is given by:[8]

$$U_{col} = l_{arc} E.$$  \hspace{1cm} (2.3)

It has been reported that for GTA welding with argon and helium shielding gas the value of $E$ is in the order of 0.5 V mm$^{-1}$ to 1 V mm$^{-1}$ and 1 V mm$^{-1}$ to 4 V mm$^{-1}$ respectively.[9] For GMA welding of carbon steel, a value of $E$ in the range of 0.7 V mm$^{-1}$ to 1 V mm$^{-1}$ has been reported.[10,11]

It should be noted that research in the past showed that the electrical field strength along the arc column is not constant. Allum,[12] for instance, reported that in GTA welding with a current of 100 A ($p = 1$ atm), the measured $E$ decreases from approximately 2.5 V mm$^{-1}$ at about 1 mm beneath the electrode to approximately 0.3 V mm$^{-1}$ at about 8 mm from the electrode (figure 2.6). Calculations by Wu et al.\cite{13} gave a similar trend.

![Figure 2.6 Electric field strength of arc column as a function of axial distance from the cathode.\cite{12}](image)
2.1.4 Forces in arc welding

During arc welding various forces act on the weld pool and, in the case of welding with a consumable wire, also on the liquid droplet. These forces influence the mode of the metal transfer and the motion of the liquid metal in the weld pool and the droplet, which in turn can have an effect on the process stability, on the weld penetration, and on the bead shape. These forces include the gravitational forces, the surface tension force, the electromagnetic Lorentz force and the force due to the plasma jet.\cite{14-16}

With regard to the weld pool, these forces will basically generate two types of convective flow, an outward flow and an inward flow. The outward liquid flow produces a shallow penetration and the inward liquid flow yields a deep penetration.\cite{15}

The gravitational force is proportional to the density of the liquid metal. Variation of liquid metal density during welding occurs due to the different local temperature in the weld pool. The gravitational force induces an outward liquid flow in the weld pool.\cite{17}

The surface tension is dependent on temperature. The temperature coefficient of the surface tension $d\gamma/dT$ can change due to the presence of surface active elements such as oxygen and sulphur. A negative surface tension temperature coefficient (the surface tension decreases with increasing temperature) will induce an outward fluid flow. On the other hand, a positive surface tension temperature coefficient (the surface tension increases with temperature) will induce an inward fluid flow.\cite{18}

The Lorentz force during welding is generated by the interaction between the electromagnetic field and the welding current. In the weld pool, the Lorentz force induces an inward liquid flow.\cite{17} In the arc column, the Lorentz force will accelerates the plasma towards the weld pool. The magnitude of this arc force $F_{arc}$ is found to be proportional to the square of the welding current $I$ as given by:\cite{19,20}

$$F_{arc} \propto I^2.$$\hspace{1cm} (2.4)

The momentum transfer of the impinging plasma jet on the weld pool will depress the weld pool surface. Lin and Eager\cite{21} reported that the arc pressure $P_{arc}$ generated on the weld pool surface can be expressed as:
\[ P_{arc} = \frac{\mu_0 I^2}{4\pi^2 R^2}, \tag{2.5} \]

where \( \mu_0 \) is the magnetic permeability of free space, \( I \) the welding current and \( R \) the arc radius. After impinging on the weld pool, the plasma jet changes its direction, drags along the surface of the weld pool and creates an outward liquid flow.\cite{14}

In the case of welding with a consumable filler wire, the impact of the transferred metal transfer acts as an additional driving force that control the liquid flow in the weld pool and can overrule other forces.\cite{22}

With regard to the liquid droplet, the acting forces manifest as retaining or detaching forces. According to the static force balance theory, the drop detaches from the electrode when the sum of the detaching forces exceeds the retaining forces.\cite{16,23} The gravitational force acts as a detaching force when welding in the horizontal position (PA position). The surface tension force acts principally as a retaining force although it promotes droplet detachment at the final stage of the metal transfer process. Depending on the welding current distribution in the metal droplet, the Lorentz force may act as a detaching force or a retaining force. When the current diverges in the droplet, a situation that can be obtained with a high current level, the Lorentz force creates a detaching force. In the case that the current converges, as obtained with low currents, the electromagnetic force acts as a retaining force. The plasma drag force acts as a minor detaching force.\cite{24}

2.2 Weld pool oscillation

2.2.1 Weld pool oscillation during autogenous GTA welding

Weld pool oscillation can be triggered by locally applying an external force on the pool. In the case of GTA welding, the most common method to trigger this oscillation is superimposing a high current pulse on the welding current. As suggested by equation (2.4), the arc force increases proportionally to the square of the pulse current. During the high current period the high arc force depresses the weld pool until a balance is built up between the pressure generated by the arc and the pressure due to surface tension and gravity. When
the welding current switches back to its base level, the arc pressure reduces and
the surface tension and gravity force the weld pool surface towards its
equilibrium position triggering oscillation. Pictures of weld pool oscillation
triggered by pulsing the welding current during GTA welding are shown in
figure 2.7.

![Weld pool oscillation](image-url)

Figure 2.7  Weld pool oscillation triggered by superimposing a high current
pulse on the welding current ($I_t$ = trigger current, $I_b$ = base current, $t_t$ = trigger current duration and $t_b$ = base current duration).

Investigations show that the weld pool can oscillate in various modes,
some of which being more dominant than others. Xiao and den Ouden\cite{25} proposed that in a partially penetrated weld pool only two modes are dominant. One of them is an axisymmetric oscillation with respect to the weld pool geometrical centre and the other is a non-symmetrical oscillation, \textit{i.e.} a sloshy oscillation. Xiao and den Ouden\cite{25} also proposed that in the fully penetrated
case the weld pool oscillation is dominated by an axisymmetric oscillation mode. The occurrence of a sloshy oscillation mode in a full penetration weld pool was suggested by Yoo and Richardson, and Maruo and Hirata.\[26,27\] These dominant oscillations are shown schematically in figure 2.8.

To date, there are no standard terms for classifying the oscillation modes. The terms used in this thesis follow those used by Xiao\[25\] in which the axisymmetric and the sloshy oscillation mode of partially penetrated weld pools are designated as mode 1 and mode 2 respectively, and the axisymmetric oscillation mode of fully penetrated weld pools is designated as mode 3. It should be noted that Xiao did not report the occurrence of the sloshy oscillation in fully penetrated weld pools in her work. To distinguish it from the sloshy oscillation of partially penetrated weld pools, in this thesis the sloshy oscillation of a fully penetrated weld pool is designated mode 2f.

<table>
<thead>
<tr>
<th>Partial penetration</th>
<th>Full penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top view</td>
<td>Side view</td>
</tr>
<tr>
<td>mode 1</td>
<td>+</td>
</tr>
<tr>
<td>mode 2</td>
<td>-</td>
</tr>
<tr>
<td>mode 3</td>
<td>+</td>
</tr>
</tbody>
</table>

Figure 2.8 Schematic illustration of dominant weld pool oscillation modes.\[25,26\]

Partially penetrated weld pools

A number of analytical models predicting the oscillation frequency of partially penetrated weld pools have been developed (see table 2.1).
Table 2.1 Mathematical oscillation models for partially penetrated weld pools.

<table>
<thead>
<tr>
<th>Model</th>
<th>Mode 1</th>
<th>Mode 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maruo-Hirata</strong></td>
<td>$f = \frac{1}{2\pi} \sqrt{gk + \frac{\gamma}{\rho} k^3} \tanh(kh)$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$k = 5.520 \left(\frac{D}{2}\right)^{-1}$</td>
<td>$k = 3.832 \left(\frac{D}{2}\right)^{-1}$</td>
</tr>
<tr>
<td><strong>Xiao-den Ouden</strong></td>
<td>$f = 5.84 \left(\frac{\gamma}{\rho}\right)^{1/2} D_{eq}^{-3/2}$</td>
<td>$f = 3.37 \left(\frac{\gamma}{\rho}\right)^{1/2} D_{eq}^{-3/2}$</td>
</tr>
<tr>
<td></td>
<td>$D_{eq} = \frac{D^2}{W_t} L_t$</td>
<td></td>
</tr>
<tr>
<td><strong>Hu-den Ouden</strong></td>
<td>$f = \frac{1}{2\pi} \left(\frac{\gamma}{\rho}\right)^{1/2} \left(\frac{2N_l}{W_t}\right)^{3/2}$</td>
<td></td>
</tr>
<tr>
<td><strong>Barnett et al.</strong></td>
<td>$f = 3.16 \sqrt{\frac{8}{3} \frac{\gamma}{\pi m}}$</td>
<td>$f = 2 \sqrt{\frac{8}{3} \frac{\gamma}{\pi m}}$</td>
</tr>
</tbody>
</table>

Maruo and Hirata\textsuperscript{[28]} used a potential flow approach to model oscillation mode 1 and mode 2 as given in equation (2.6). A weld pool having a crater area $A$ and a penetration depth $H$ is simulated as a circular basin with a diameter $D$ and a uniform weld depth $h$ so that the surface area and the volume of the weld
pool equal those of the circular basin (figure 2.9). In equation (2.6), \( f \) is the oscillation frequency, \( \gamma \) the surface tension, \( \rho \) the density of the liquid metal, \( g \) the acceleration due to gravity and \( k \) the wave number. The value of \( k \) is dependent on the oscillation mode and on the shape of the weld pool. In the case of circular weld pools, \( k \) is \( 5.520/(D/2) \) and \( 3.832/(D/2) \) for oscillation mode 1 and mode 2 respectively.

Using the same approach used by Maruo and Hirata and neglecting the influence of the gravitational force, Xiao and den Ouden\(^{29,30}\) derived simplified equations for oscillation mode 1 and mode 2 (equations (2.7) and (2.8)). These equations can be used to predict the oscillation frequency of elliptical weld pools taking \( D_{eq} \) as the diameter of a circle, which has an area equal to that of the elliptical weld pool (equation (2.9)). Note that \( L_t \) and \( W_t \) in equation (2.9) are the pool length and the pool width respectively.

More recently, Hu and den Ouden\(^{31}\) made use of the Mathieu function and proposed a solution to predict the frequency of an elongated weld pool that oscillates in mode 2 as expressed by equation (2.10). In this formula \( N_1 \) is the eigenvalue for the second lowest oscillation mode and is dependent on the ratio between the major axis (the length) \( L_t \) and the minor axis (the width) \( W_t \) of an elliptic weld pool. For a circular weld pool, \( N_1 \) is 3.83 so that equation (2.10) is identical to equation (2.8).
Another expression for the weld pool oscillation frequency was derived based on the Legendre polynomial formulation for weld pools having a spherical or approximately spherical geometry as in a liquid droplet.\cite{32,33} In this approach, the oscillation frequency of mode 1 and mode 2 can be predicted using equation (2.11) and (2.12) respectively. In these equations \( m \) is the mass of the liquid metal. Having the mass for a circular weld pool equal to \( \pi D^2 h \rho / 4 \) (see figure 2.9), equations (2.11) and (2.12) can be rewritten as equations (2.13) and (2.14) respectively.

\[
f = 3.285 \left( \frac{\gamma}{\rho h} \right)^{1/2} D^{-1}
\]  
\hspace{1cm} (2.13)

\[
f = 2.079 \left( \frac{\gamma}{\rho h} \right)^{1/2} D^{-1}
\]  
\hspace{1cm} (2.14)

Fully penetrated weld pools

Table 2.2 summarizes the analytical models predicting the oscillation frequency of a fully penetrated weld pool.

Kotecki et al.\cite{34} proposed a model based on the vibration of a stretched membrane to predict the surface tension of the liquid metal. Their model has a similar form as equation (2.15). Zacksenhouse and Hardt\cite{35} developed a model where the weld pool is considered as a mass-spring system. This approach also results in an expression, which is similar to equation (2.15). Xiao and den Ouden\cite{29} extended Kotecki’s work by using a tapered weld pool with an equivalent diameter \( D_{eq} \), which is defined as the diameter of a cylinder, the volume of which is equal to the volume of the tapered weld pool with a bottom pool diameter of \( D_b \) and a top pool diameter of \( D_t \) (equation (2.16)).

Maruo and Hirata\cite{27} derived the natural oscillation frequencies of circular fully penetrated weld pools using the velocity potential approach. For a weld pool in a thin plate, their model is given by equation (2.17). For circular weld pools that oscillate in an axisymmetrical and in a sloshy motion, \( k \) is \( 2.405/(D/2) \) and \( 3.832/(D/2) \) respectively.
Yoo and Richardson\cite{26} used an energy approach to predict the oscillation frequency of fully penetrated weld pools with the shape of a tapered cylinder and an elliptical free surface. For oscillation mode 3 this frequency is represented by equation (2.18). In this equation, $e$ represents the eccentricity as defined by equation (2.19), $L_t$ the length of the weld pool top surface, $L_b$ the length of the pool bottom surface, $W_t$ the width of the pool top surface and $W_b$ the width of the pool bottom surface. In the case of a cylindrical weld pool shape, equation (2.18) can be written as equation (2.20).

### Table 2.2 Mathematical oscillation models for fully penetrated weld pools.

- **Kotecki**\cite{34}, Zacksenhouse-Hardt\cite{35} and Xiao-den Ouden\cite{29}  
  \[
  f = \frac{1.08}{D} \left( \frac{\gamma \rho H}{\gamma} \right)^{1/2} \quad (2.15)
  \]
  \[
  D_{eq}^2 = \frac{1}{3} (D_t^2 + D_t D_b + D_b^2) \quad (2.16)
  \]

- **Maruo-Hirata**\cite{27}  
  \[
  f = \frac{1}{2\pi} \sqrt{-\frac{2g}{H} + \frac{2\gamma k^2}{\rho H}} \quad (2.17)
  \]
  \[
  k = 2.405 (D/2)^{-1}
  \]
  \[
  k = 3.832 (D/2)^{-1}
  \]

- **Yoo-Richardson**\cite{26}  
  \[
  f = \frac{1}{\pi W_t} \left[ 2(2 - e) \left( \frac{W_b}{W_t} \right)^3 + \frac{W_b}{W_t} \right] \left( \frac{\gamma}{\rho H} \right)^{1/2} \quad (2.18)
  \]
  \[
  e = \left( 1 - \frac{W_t}{L_t} \right)^{1/2} \quad (2.19)
  \]
  \[
  f = \frac{0.9}{D} \left( \frac{\gamma}{\rho H} \right)^{1/2} \quad (2.20)
  \]

- **Hu-den Ouden**\cite{31}  
  \[
  f = \frac{1}{2\pi} \left( \frac{8\gamma}{\rho H} \right)^{1/2} \left( \frac{N_0}{W_{avg}} \right) \quad (2.21)
  \]
Hu and den Ouden\cite{31} suggested that the elliptical shape of the weld pool changes both the equivalent diameter and the oscillation behaviour of the weld pool. Using the Mathieu function, they proposed that the frequency of a fully penetrated weld pool that oscillates in mode 3 can be given by equation (2.21). In this equation, $N_0$ is the eigenvalue for the lowest oscillation mode, the value of which is 2.40 for a circular weld pool and 1.81 for an elongated weld pool with $W_t/L_t = 0.4$.\cite{31,36} Note that for a circular weld pool equation (2.21) is identical to equation (2.15).

**Evaluation of the weld pool oscillation frequency**

In figure 2.10 the frequencies of different oscillation modes calculated using the models developed by Maruo and Hirata (equation (2.6) and (2.14)) are presented for a circular weld pool in 3 mm thick plate. The oscillation frequencies are plotted as a function of the pool diameter. The material properties used in the calculation are given in table 2.3. Figure 2.10 shows that the oscillation frequency decreases with increasing pool diameter. For a similar pool diameter, the frequency of mode 1 oscillation is the highest compared with other oscillation modes, whilst the frequency of mode 3 oscillation is the lowest. With respect to mode 2 oscillations, the frequency of mode $2f$ oscillations is lower but approaching that of mode 2 when the equivalent diameter is approximately 14 mm.

| Material properties to calculate weld pool oscillation frequencies.\cite{31} |
|---------------------------------|---------------------------------|
| surface tension $\gamma$       | 1.2 N m$^{-1}$                 |
| density $\rho$                 | 7500 kg m$^{-3}$               |

The mode 1 and mode 2 oscillation frequencies calculated using the various solutions in table 2.1 are compared in figures 2.11 and 2.12 respectively. Note that the calculations were made for circular weld pools using the material properties given in table 2.3. In figure 2.11 mode 1 oscillation frequencies are plotted as a function of the weld pool diameter. The figure shows that the frequencies predicted by Xiao and den Ouden match those predicted by Maruo and Hirata. The differences between both predictions are up to 1.2 % for a weld pool with a diameter from 3 mm to 14 mm. This indicates that the influence of gravity is negligible. Figure 2.11 also shows that compared with the Maruo and Hirata prediction, the oscillation frequencies predicted by Barnett are lower for a pool diameter smaller than 6 mm, but are higher for a pool diameter larger than 6 mm.
Figure 2.10 Frequency of different weld pool oscillation modes as a function of weld pool diameter calculated using Maruo and Hirata models, \textit{i.e.} equations (2.6) and (2.17).

Figure 2.11 Frequency of oscillation mode 1 calculated using Maruo and Hirata, Xiao and den Ouden, and Barnett solutions.

Figure 2.12 shows the predicted oscillation frequencies as a function of the weld pool diameter for mode 2 oscillation. As in figure 2.11, the calculations were made for the case of circular weld pools. The Hu and den
Ouden solution for this pool geometry gives almost identical frequencies to those of the Xiao and den Ouden solution. Figure 2.12 shows that Xiao and den Ouden predict oscillation frequencies, which match those predicted by Maruo and Hirata. Differences up to 6% are found between both predictions for a weld pool with a diameter from 3 mm to 14 mm. Figure 2.12 also shows that the oscillation frequencies predicted by Barnett deviate (lower of about 25% for a weld pool diameter of 3 mm and higher by a factor of 54% for a weld pool diameter of 14 mm) from those predicted by Maruo and Hirata.

Comparison of the frequencies of mode 3 oscillations predicted by the various models given in table 2.2 is presented in figure 2.13. The calculations were made for the case of circular weld pools on 3 mm thick plate using the material properties given in table 2.3. As in the mode 2 oscillation case, the Hu and den Ouden solution gives identical frequencies to those of the Xiao and den Ouden solution. Figure 2.13 shows that the Xiao and den Ouden solution matches very well with the Maruo and Hirata solution for a small pool diameter but the deviation enlarges for larger weld pools. The oscillation frequencies predicted by Yoo are 16% lower than those predicted by Xiao and den Ouden.

![Figure 2.12 Frequency of oscillation mode 2 calculated using Maruo and Hirata, Xiao and den Ouden, and Barnett solutions.](image-url)
2.2.2 Numerical models of weld pool oscillation

In addition to the analytical approach, weld pool oscillation during GTA welding has also been studied using a numerical approach. This is mainly based on a Volume of Fluid (VOF) method. Ko et al.,\cite{37,38} for instance, found that the effect of arc pressure on the depression of the weld surface is negligible at low currents but should be taken into account at high currents (above 200 A). Hirata et al.,\cite{39} developed a 3D numerical model, which made it possible to calculate and visualize liquid metal flow having a free surface in elliptical GTA weld pools. Their study demonstrated that the surface deformation and the oscillation mode of the pool are dependent on both the pressure distribution and the pool shape. The study also demonstrated that the weld pool oscillation frequency calculated with the numerical model decreases with increasing pool size, similar to that calculated with the analytical solutions. The results of the numerical solution, however, give lower oscillation frequencies in comparison to the analytical method. This difference is expected to be due to the assumptions used in the analytical method and/or numerical errors from the finite difference approximation in the numerical method.
2.2.3 Weld pool oscillation during GTA welding with filler wire addition

In the case of cold-wire GTA welding little is known about weld pool oscillation phenomena. Aendenroomer\cite{40} showed that the cold-wire GTA weld pool can be triggered into oscillation not only by the trigger current but also by the impact of the metal droplet transferred to the weld pool.

2.2.4 Weld pool oscillation during GMA welding

In short-circuit GMA welding, weld pool oscillation is triggered by the arc re-ignition directly after the rupture of the liquid bridge.\cite{24} During short-circuiting, a liquid bridge is formed between the electrode and the weld pool. In this period the voltage drops to the minimum value while the welding current increases sharply. Due to the increase of the current, the electromagnetic Lorentz force also increases. This force has a pinching effect that results in necking and finally rupture of the liquid bridge. When the liquid bridge ruptures, the arc is re-ignited. The re-ignition of the arc results in a sudden increase of the arc pressure that depresses the weld pool. Subsequently, the welding current reduces to its original level, the arc pressure also reduces and the weld pool surface is brought into oscillation by the surface tension and gravity. Observation of a complete oscillation cycle of the weld pool during S-GMA welding is, however, difficult since subsequently the pool surface touches the liquid droplet and another short-circuit occurs.

In the case of globular transfer in stationary GMA welding, Fan and Kovacevic\cite{41} observed that weld pool oscillation can be triggered by the impingement of the droplet. Fan and Kovacevic also observed that the amplitude of the weld pool oscillation decreases gradually with time. Zhu et al.\cite{42} simulated the coupled transport phenomena between the electrode, the arc plasma, and the weld pool during stationary GMA welding of AISI 304 stainless steel with a constant current. Under the welding conditions used in their work, their calculation resulted in a droplet detachment frequency of 63 Hz. With this droplet detachment frequency, a complete cycle of weld pool oscillation could not be observed due to impingement of the subsequent droplet before the weld pool ‘bounced’ back. Recently, Hu et al.\cite{43} extended the model to 3D moving GMA welding. They showed that a crater was opened (the weld pool was depressed) by the impingement of the droplet and then closed (the depressed weld pool surface raised) due mainly to the hydrostatic force. Again,
a complete cycle of weld pool oscillation could not be observed due to a relatively high droplet impingement frequency (65 Hz).

2.2.5 Penetration sensing and control based on weld pool oscillation

An essential element of oscillation based penetration sensing is the difference between the oscillation frequencies of partially penetrated weld pools and fully penetrated weld pools. By monitoring the weld pool oscillation and the application of a simple feedback system, the welding current can be adjusted to keep the oscillation frequency constant and thus maintain a correct weld penetration.

Three approaches of oscillation based penetration sensing have been developed by previous researchers, these are: free response approach, resonance approach and synchronous approach. In the free response approach the oscillation of the weld pool is triggered by locally applying an external force on the pool at a constant (low) frequency. The subsequent trigger pulse is applied after the oscillation amplitude decayed to a negligible level so that the weld pool oscillations are not disturbed by the oscillation triggered by the previous pulse. Commonly, weld pool oscillation is triggered by superimposing a high pulse on the welding current.\textsuperscript{[31,44,45]} Another way to trigger this oscillation is pulsing the shielding gas flow rate as has been used by Suga \textit{et al.}\textsuperscript{[46]} Two approaches to determine the state of the weld penetration have been adopted: the single frequency approach\textsuperscript{[31]} and the double frequency approach.\textsuperscript{[44]}

In the single frequency approach, a pre-set oscillation frequency is determined as a reference to control the process. This frequency corresponds to a full penetration condition. During welding the measured oscillation frequency is compared with the reference frequency. When these values are not equal, a feedback system adjusts the welding current, and thus the pool size, so that the oscillation frequency approaches the pre-set value.

The double frequency approach is developed based on the principle of pulsed GTA welding where a full penetration weld is produced during the pulse current period and a partial penetration weld is obtained during the base current period. Trigger pulses are applied at the beginning of both the pulse and the base periods. In this approach, three different penetration states can be distinguished. Firstly, partial penetration occurs when high oscillation frequencies are detected during both the pulse and the base periods. Secondly, a
Correct weld penetration is obtained when high oscillation frequencies are detected during the base period and low oscillation frequencies during the pulse current period. Finally, over-penetration is indicated by the occurrence of low oscillation frequencies during both the pulse current and the base current periods. The advantage of the double frequency approach is that a pre-set oscillation frequency is not required since the system can detect the correct penetration state by itself.

In the resonance approach a sinusoidal current waveform with a frequency corresponding to the oscillation frequency of a fully penetrated weld pool is used for welding.\cite{47} Correct penetration is obtained when a resonance situation occurs (the frequency of the weld pool oscillations is equal to the frequency of the current waveform). The vertical displacements of the pool and the voltage variations reach their maximum. Wang et al.\cite{47} have showed the potential of this approach for overlap spot welding.

In the synchronous approach the trigger current pulse is synchronised with the oscillations of the weld pool.\cite{32} Andersen et al., for instance superimposed the pulse to trigger weld pool oscillation every four oscillation cycles. In this way a lower trigger current can be used in comparison to the free response approach.

A practical way to measure the frequency of weld pool oscillations is monitoring the arc voltage. During weld pool oscillations the arc length changes periodically. The periodic change of the arc length is reflected on the voltage signals given that both variables are proportional to each other, as described in section 2.1.3. Another way to monitor weld pool oscillation is by monitoring the intensity of the arc light since, like the arc voltage, the arc light intensity is also dependent on the arc length. Yoo\cite{26} reported that the arc light sensor has a higher sensitivity compared with the voltage sensor. Barborak\cite{48} observed that the sensing through arc voltage can reliably be utilized for travel speeds up to 3.83 mm s\(^{-1}\), whilst the arc light sensor can be used for speeds as high as 6.35 mm s\(^{-1}\). In comparison with voltage measurements, however, arc light monitoring is less practical since it requires additional equipment and needs a larger access area.

Typical welding parameters for oscillation based penetration sensing are given in table 2.4. Successful results of penetration sensing and control have been reported regarding autogenous GTA welding.
Table 2.4 Typical welding parameters for oscillation based penetration sensing.

<table>
<thead>
<tr>
<th></th>
<th>Wang et al.(^{[47]})</th>
<th>Andersen et al.(^{[50]})</th>
<th>Woodward and Norish(^{[49]})</th>
<th>Barborak and Richardson(^{[48]})</th>
<th>Aendenroomer(^{[40]})</th>
<th>Hu and den Ouden(^{[31]})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding current</td>
<td>40 A</td>
<td>65A - 130 A</td>
<td>15 - 27.5 A</td>
<td>20 – 140 A</td>
<td>90 - 105 A</td>
<td></td>
</tr>
<tr>
<td>Trigger current</td>
<td>Base current + 30 A</td>
<td>Base current + 50 A</td>
<td>125 A</td>
<td>Base current + 50 - 100 A</td>
<td>150 - 250 A</td>
<td>300 A</td>
</tr>
<tr>
<td>Trigger frequency</td>
<td>64 Hz Resonance approach</td>
<td>Synchronised pool/trigger frequency ratio 4</td>
<td>2 Hz</td>
<td>1 Hz</td>
<td>Applied at the initial of both the pulse and the base periods</td>
<td>2 - 2.5 Hz</td>
</tr>
<tr>
<td>Trigger time</td>
<td>15 ms</td>
<td>10 ms</td>
<td>5 ms</td>
<td>3 ms</td>
<td>3 ms</td>
<td></td>
</tr>
<tr>
<td>Travel speed</td>
<td>Step travelling, about 1.5 s/step.</td>
<td>0.8 mm s(^{-1})</td>
<td>1.5 mm s(^{-1})</td>
<td>0.85 - 6.35 mm s(^{-1})</td>
<td>0.5 - 2 mm s(^{-1})</td>
<td>2 - 3 mm s(^{-1})</td>
</tr>
<tr>
<td>Shielding gas</td>
<td>Ar</td>
<td>Ar</td>
<td>Ar+10% H(_2)</td>
<td>He</td>
<td>Ar</td>
<td>Ar+5% H(_2)</td>
</tr>
<tr>
<td>Electrode tip</td>
<td>45°</td>
<td>30°</td>
<td>30°</td>
<td>60°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arc length</td>
<td>2 - 3 mm</td>
<td>1.3 mm</td>
<td>1.5 mm</td>
<td>1 - 1.5 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Steel 1015</td>
<td>Steel 1020</td>
<td>AISI 316L</td>
<td>AISI 304</td>
<td>AISI 304 Fe 360</td>
<td>AISI 316 AISI 304 Fe 360</td>
</tr>
<tr>
<td>Sensor</td>
<td>Voltage</td>
<td>Light</td>
<td>Voltage</td>
<td>Voltage Light</td>
<td>Voltage</td>
<td>Voltage</td>
</tr>
</tbody>
</table>
2.3 Droplet oscillation

2.3.1 Pendant droplet oscillation

As is the case for weld pool oscillations, pendant droplet oscillation during welding can be triggered by superimposing a high amplitude current pulse on the welding current.\textsuperscript{[51]} The principle of this approach is based on the action of the forces generated during welding on the pendant droplet. As mentioned in section 2.1.4, according to the static force balance theory, the drop detaches from the electrode when the sum of the detaching forces exceeds the retaining forces.\textsuperscript{[16,23]} In conventional P-GMA welding, the peak current is intended to detach the droplet. Therefore, this peak current must be higher than the critical spray transition current and long enough so that a droplet can be detached in a single pulse. If the peak time is too long, several droplets may be detached in a single pulse, while if the peak time is too short several pulses are required to detach one droplet. In the latter case the droplet can be excited into oscillation. A schematic illustration of pendant droplet oscillation triggered by a current pulse is shown in figure 2.14. It can be seen in the figure that during the peak current, the downward electromagnetic force, generated by the pulse, drags the droplet down. When the current is switched to the base level the electromagnetic force decreases significantly. In this situation the droplet jumps upward in order to establish a new equilibrium position and is excited into oscillation due to the surface tension of the melted droplet and gravity.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2.14.png}
\caption{Schematic drawing of pendant droplet oscillation triggered by a welding current pulse ($I_p$ = peak current, $I_b$ = base current, $t_p$ = peak current duration and $t_b$ = base current duration).}
\end{figure}
Pendant droplet oscillation during welding has been investigated both experimentally and theoretically. Choi et al.\cite{52} used a dynamic force balance model to analyse metal transfer during GMA welding and considered an ellipsoidal droplet as a mass-spring system. With this model they estimated an oscillation frequency of 90 Hz and 121 Hz for a pendant droplet with a diameter of 2.69 mm and 2.12 mm respectively, which were 10%-40% higher than the experimental results. It was explained that the discrepancies could be due to the flow momentum within the drop. Using a similar approach to Choi et al.\cite{52}, Wu et al.\cite{53} described the influence of the sudden change in the welding current on the dynamics of the pendant droplet. Their predicted oscillation amplitude is larger than the experimental results, but the predicted frequencies match relatively well. Wang et al.\cite{54} developed a numerical model to simulate the metal transfer process during GMA welding and found that the pendant droplet might oscillate after droplet detachment due to the unbalanced surface tension of the liquid that remains at the wire tip. More recent modelling work on pendant droplet oscillation during GMA welding was carried out using the VOF and the continuum surface force method by Wang et al.\cite{55} and Hirata et al.\cite{56}. They developed dynamic models in order to simulate the metal transfer process to predict the oscillation frequency of pendant droplets as a function of droplet size. The oscillatory behaviour of the pendant droplet after the current pulse in P-GMA welding has also been observed by means of a comprehensive model by Hu and Tsai.\cite{57} Chen et al.\cite{58} developed an analytical model, again, based on a mass-spring system to explain quantitatively the droplet oscillation and detachment process in modified pulsed-current GMA welding.

### 2.3.2 Free droplet oscillation

Subramaniam et al.\cite{59} reported that during GMA welding the detached droplet may oscillate during its travel to the weld pool. Prior to detachment, the droplet at the wire tip is initially elongated due to the electromagnetic forces as already explained. Immediately after detachment, the surface tension causes the droplet to oscillate in its lowest oscillation mode, which is alternately elongated (prolate) or compressed (oblate) along its axis of symmetry (figure 2.15).

Oscillation of a free spherical droplet under non-arc conditions has been described as early as the late 1870s.\cite{60} It was found that the oscillation frequency of a liquid mass with a spherical shape, which oscillates symmetrically about an axis, can be expressed in the form given in equation (2.22). In this equation, $\tau$ is the period of one oscillation cycle and $V$ is the volume of the droplet.
In the case of arc welding, modelling work on free droplet oscillations has not been performed extensively. Subramaniam et al.\cite{59} for instance, investigated the oscillation of a steel droplet during GMA welding using the Rayleigh equation\cite{60} derived for non-arc conditions. For welding with Ar+O$_2$ and Ar+CO$_2$ shielding gases, they observed that for a free droplet with a diameter from 1.35 mm to 1.73 mm the oscillation frequency decreases from 345 Hz to 250 Hz. Recently, while developing a two-dimensional numerical model to simulate the metal transfer process, Wang et al.\cite{54} also showed the occurrence of free droplet oscillation.

Summary

During arc welding, the weld pool and the metal droplet can be brought into oscillation due to an externally applied force. In the autogenous GTA welding process, for instance, weld pool oscillation can be triggered by superimposing a short period pulse on the welding current. When a filler wire is added during welding, as in cold-wire GTA welding or GMA welding, the weld pool can also be triggered into oscillation by the momentum of the liquid metal injected into the weld pool. In addition, in the case of S-GMA welding, the oscillation of the weld pool can be triggered by the arc re-ignition directly after the rupture of the liquid bridge. The pendant droplet and the free droplet oscillations during GMA welding have been observed and were reported to be caused by the actions of the electromagnetic force and the surface tension.
Experimental work in the past has shown that various weld pool and droplet oscillation modes exist. A number of analytical models for weld pool and droplet oscillations frequency calculations have been developed following several approaches. These models show that for each oscillation mode, the oscillation frequency is dependent on the weld pool or droplet geometry and the material properties, particularly the surface tension and the density of the liquid metal. These models also show that the oscillation frequency decreases with increasing weld pool and droplet size. In addition to the analytical approach, weld pool oscillation during GTA welding has also been studied using a numerical approach. This enables the visualization of the liquid metal flow and makes the dynamic behaviour of the weld pool clearer. At present the work on numerical modelling of weld pool and droplet oscillations is progressing. Further improvement of the models is still required regarding the accuracy of the predictions.

Past observations on weld pool oscillation were mainly carried out during autogenous GTA welding. The research on weld pool oscillation has lead to the development of oscillation based penetration sensing. The sensing system is based on the difference between the oscillation frequency of the partially and the fully penetrated weld pools. By monitoring the pool oscillation frequency in combination with applying a feedback system, the welding current can be adjusted to maintain a correct weld penetration. A variety of penetration sensing methods has been invented namely the single frequency approach, the double frequency approach, the resonance approach and the synchronous approach. Only a few experimental observations of weld pool oscillation during cold-wire GTA welding and GMA welding have been reported. Therefore, further study of weld pool oscillation during arc welding with filler wire addition is required to better understand the phenomenon and to investigate its potential for industrial application.
References


Chapter 3:
Liquid metal behaviour during cold-wire GTA welding

3.1 Introduction

In cold-wire GTA welding, a consumable filler wire is introduced to the weld pool without being preheated. The metal wire is melted due to the heat produced by the welding arc. As the molten wire is transferred to the weld pool, the physical and chemical condition of the liquid metal in the weld pool can change dependent on the chemical composition and the amount of metal transferred. It can be expected that modification of the liquid metal conditions influences the oscillatory behaviour of the weld pool.

Of the few available publications on weld pool oscillation during cold-wire GTA welding, Aendenroomer[1] reported that the transfer of the droplet to the surface of the weld pool can trigger the weld pool into oscillation. He also reported that weld penetration sensing by means of oscillation frequency analysis is possible during GTA welding with cold-wire supply, but that sensing in this case is less accurate than in the case of autogenous GTA welding. His experiments showed that the oscillation frequency of the weld pool in the case of cold-wire GTA welding is characterised by considerable scatter. It was explained that this scatter is caused by the influence of droplet transfer on the size and the temperature of the weld pool, which brings the mode 1 frequency range closer towards the mode 3 frequency range. No solution, however, was given to avoid these disturbing phenomena. Unlike Aendenroomer, who was able to measure the oscillation frequency of the weld pool during cold-wire GTA welding by applying Fast Fourier Transform (FFT) analysis of the voltage signals, Wohlfahrt et al.[2] reported that the weld pool oscillation signal during cold-wire GTA welding could not be detected. Apparently, more insight on this
subject is required to form a solid basis to develop a robust weld penetration control system for cold-wire GTA welding.

The study described in this chapter deals with monitoring weld pool oscillation during cold-wire GTA welding. The main objective of this study is to obtain a better understanding of the influence of cold-wire addition on the oscillatory behaviour of the weld pool with emphasis on the relationship between weld pool oscillation behaviour and the electric signals. The study is focused on the uninterrupted and the interrupted bridging transfer, since in most cases the metal transfer during cold-wire GTA welding takes place in these transfer modes. Autogenous GTA welding experiments have been carried out for comparison purpose.

3.2 Experimental procedure

3.2.1 Materials and consumables

GTA welding experiments were carried out on stainless steel AISI 316L tubes with an outer diameter of 48.3 mm and a wall thickness of 2.1 mm. The filler wire was ER316LSi with a diameter of 0.8 mm. The shielding gas was a mixture of Ar with 5 vol. % H\textsubscript{2} with a flow rate of 11 l min\textsuperscript{-1}, whilst the backing gas was Ar with a flow rate of 4 l min\textsuperscript{-1}. The chemical compositions of the base material and the filler wire are listed in table 3.1.

<table>
<thead>
<tr>
<th>Chemical Composition (%)</th>
<th>AISI316L</th>
<th>ER316LSi</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Cr</td>
<td>16.0-18.0</td>
<td>18.0-20.0</td>
</tr>
<tr>
<td>Ni</td>
<td>10.0-14.0</td>
<td>11.0-14.0</td>
</tr>
<tr>
<td>Mo</td>
<td>2.0-3.0</td>
<td>2.0-3.0</td>
</tr>
<tr>
<td>Mn</td>
<td>2.0</td>
<td>1.0-2.5</td>
</tr>
<tr>
<td>Si</td>
<td>1.00</td>
<td>0.65-1.00</td>
</tr>
<tr>
<td>P</td>
<td>0.045</td>
<td>0.030</td>
</tr>
<tr>
<td>S</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Cu</td>
<td>N/A(**)</td>
<td>0.75</td>
</tr>
</tbody>
</table>

(*) Single values are maximum values.
(**) Not available

3.2.2 Welding system and welding conditions

An experimental arrangement as schematically shown in figure 3.1 was used to produce autogenous and cold-wire GTA welds. A MacGregor transistorised power source (figure 3.2a) capable of supplying a maximum current of 500 A was operated in a constant current characteristic mode. A
tungsten with 2 wt. % thoria electrode was used, with a diameter of 2.4 mm and a tip angle of $60^\circ$ (figure 3.2b).

Figure 3.1 Schematic drawing of the experimental arrangement.

Figure 3.2 a) Front view of the MacGregor power source and the cooling unit, b) close-up of the welding electrode and the filler wire tip and c) overview of the experimental arrangement.
During the cold-wire GTA welding experiments, the wire was continuously fed to the front of the weld pool in such a way that the angle between the wire and the workpiece was approximately 25°. The delivery position of the filler wire could be increased to change the mode of metal transfer, from the uninterrupted to the interrupted mode, as described in section 2.1.1.

The welding arc was ignited by short-circuiting the electrode and the workpiece using a carbon stick. Longitudinal welds were produced on the tube in the flat or PA position. During welding the workpiece was travelling underneath the fixed torch. The welding conditions are listed in table 3.2. These conditions are comparable to the conditions used by Hu and den Ouden[5] (see section 2.2.5). The oscillation of the weld pool was initiated by applying trigger pulses on the welding current. A typical current waveform used during welding to trigger weld pool oscillation is presented in figure 3.3. The figure shows a square wave trigger pulse of about 300 A, with a trigger time of 3 ms and a base current of 44 A.

Table 3.2  Welding conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shielding cup size</td>
<td>no. 7 (internal dia. 11 mm)</td>
</tr>
<tr>
<td>Electrode extension below shielding cup</td>
<td>approximately 7.5 mm</td>
</tr>
<tr>
<td>Shielding gas / flow rate</td>
<td>Ar+5% H₂ / 11 l min⁻¹</td>
</tr>
<tr>
<td>Backing gas / flow rate</td>
<td>Ar / 4 l min⁻¹</td>
</tr>
<tr>
<td>Arc length</td>
<td>1.5 mm to 2.4 mm</td>
</tr>
<tr>
<td>Base current $I_b$</td>
<td>24 A to 66 A</td>
</tr>
<tr>
<td>Trigger current $I_t$</td>
<td>300 A</td>
</tr>
<tr>
<td>Trigger frequency $f_t$</td>
<td>2 Hz</td>
</tr>
<tr>
<td>Trigger time $t_t$</td>
<td>3 ms</td>
</tr>
<tr>
<td>Travel speed $v$</td>
<td>2.0 mm s⁻¹</td>
</tr>
<tr>
<td>Wire diameter (*)</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Wire feed rate $WFR$ (*)</td>
<td>4.6 mm s⁻¹</td>
</tr>
</tbody>
</table>

(*) in the case of cold-wire welding
3.2.3 High-speed imaging system

Monitoring of the liquid metal behaviour during welding was carried out by means of a high-speed imaging technique. For this purpose a monochrome digital high-speed video camera (Phantom V5.0, see figure 3.2c) was used. The camera was set to record 2000 pictures per second at a 216 (height) x 512 (width) pixel resolution. With this setting an event of up to 16 s can be recorded. A Schott KL 1500 light source with a halogen lamp of 150 W was used to illuminate the field of interest. A zoom lens was employed with a neutral density filter (4x). The exposure time and the aperture were selected in such a way that a maximum visibility of the weld pool was obtained. In most cases an exposure time of 10 μs and an aperture of f22 (the smallest lens opening) were selected. Analysis of the high-speed video pictures revealed the oscillation frequencies of the weld pool and droplet.

3.2.4 Monitoring and analysis of electrical welding parameters

The oscillatory behaviour of the weld pool and the droplet were also monitored using the electrical signals measured during welding. For this purpose, the arc voltage and welding current were recorded using a two-channel digital Nicolet 410 oscilloscope. The measuring time was 15.8 s and the sampling frequency was 2000 Hz. The arc voltage was measured between the
torch and the workpiece, whereas the welding current was measured by means of a current transducer.

To determine the oscillation frequency of the weld pool and the droplet, post-welding analysis was carried out by applying Fast Fourier Transforms (FFT) on the voltage signals. To perform the frequency analysis a computer program was developed using Labview software of National Instruments. The analysis was applied on the data starting from 10 ms after the end of the pulse. To satisfy the conditions for a valid FFT analysis, the number of data points \( n \) was selected to be a power of 2 and in the analysis 256 data points were taken into consideration. Before performing the FFT analysis, the DC component was removed from the voltage signals. Furthermore, the signals were filtered using a Butterworth band-pass filter, with a filter order of 6 and a cut-off frequency of 20 Hz-500 Hz and windowed using a Hanning window.\[^{[6]}\] The oscillation frequency obtained by the FFT operation has a resolution \( \Delta f \) that is dependent on the sampling rate \( S \) and the number of the data points \( n \) according to equation (3.1). In this study a resolution of 7.8 Hz in the frequency domain was obtained.

\[
\Delta f = \frac{S}{n} \tag{3.1}
\]

To correctly determine the temporal relationship between the electric signals and the corresponding phenomenon captured by the high-speed imaging technique, both monitoring techniques were synchronised.

### 3.2.5 Weld geometry and macro-structures

The length of the weld pool was determined from the weld crater, whilst the depth of penetration and the width of the weld (top and bottom) were obtained from the transverse cross-section of the solidified weld. The weld cross-sections were produced by cutting the welds and embedding the specimens in a thermoplastic resin (Technovit 4701). The specimens were then ground to a 1200 grit finish, polished to 1 \( \mu m \) and etched with Kalling (5 g of copper chloride in a solution of 100 ml ethanol (96%) and 100 ml hydrochloric acid (32%)) for about 10 s. Cross-sections and top views of the welds were observed using an Olympus SZX9 stereomicroscope and an Olympus BX60M microscope. With both microscopes the weld geometries were measured using ‘Analysis’ software from Olympus. From the measurements of the geometry,
the equivalent diameter $D_{eq}$ was calculated as described in figure 2.9 for the partial penetration case and using equation 2.16 for the full penetration case.

3.3 Results and discussion

In this section the results of observations of weld pool behaviour during autogenous GTA welding and cold-wire GTA welding with uninterrupted and interrupted bridging transfers are described and discussed. Both partial and full penetration situations are considered. The observations were performed by means of high-speed imaging. Voltage signals, which were monitored during welding, were analysed to obtain the frequency of weld pool oscillations. The results are compared with the results from visual observations and those from calculations.

3.3.1 Autogenous GTA welding

High-speed video monitoring

A number of autogenous welds were produced using the welding conditions described in table 3.2. With a base current of lower than 57 A, partial penetration was obtained. When the base current was 57 A or higher, full penetration was obtained. Visual observations using a high-speed video show that the partially penetrated weld pools oscillate in mode 2. This oscillation mode is presented in figure 3.4, which shows a weld pool produced using a welding current of 42 A. It can be seen in the figure that before the trigger pulse is applied ($t = 6619.0$ ms) the weld pool surface is relatively flat. When the trigger pulse is applied the arc pressure depresses the weld pool. The weld pool depression can be clearly seen when the current is switched back to its base level ($t = 6623.5$ ms). The oscillation mode 2 can be noted from the position of a crest, which moves to the back of the weld pool ($t = 6626.0$ ms, $6639.0$ ms and $6654.5$ ms) and to the front ($t = 6632.5$ ms, $6649.0$ ms and $6664.0$ ms). From the time interval between the successive maximum amplitudes of the weld pool underneath the electrode, the oscillation frequency is estimated to be approximately 71 Hz.
Figure 3.4 Oscillations of a partially penetrated weld pool in the case of autogenous GTA welding.

Figure 3.5 Oscillations of a fully penetrated weld pool in the case of autogenous GTA welding.
When full penetration is obtained the weld pool also oscillates in a sloshy mode. In figure 3.5, this sloshy oscillation is shown. The weld pool is produced using a base current of 57 A. The figure shows that the weld pool starts to oscillate following the depression of the weld pool by the arc pressure ($t = 9775.5$ ms). The oscillation is marked by regular changes of the crest position. At $t = 9782.0$ ms, $9809.5$ ms and $9839.5$ ms the crest is situated in the back part of the weld pool while at $t = 9793.0$ ms and $9820.0$ ms the crest is situated in the front part of the weld pool. The average frequency of the weld pool oscillation revealed from the high-speed pictures in this example was found to be 36 Hz. It is not confirmed whether the oscillation takes place in mode 2 or mode 2f due to lack of accessibility to the back side of the weld pool.

According to Xiao,\cite{7} mode 2 oscillation is promoted by an increase in travel speed, the use of argon instead of helium as shielding gas and the use of stainless steel instead of carbon steel as base materials. All these factors affect the weld pool geometry (the length-to-width ratio) and also the eccentricity of the arc with respect to the weld pool. Due to the deviation of the arc axis from the centre of the weld pool, a pressure difference exists between the front part and the back part of the weld pool. During the trigger pulse period, this pressure difference induces the front-to-back flow in the weld pool. Figure 3.6 shows a schematic top view of a weld pool, where $\theta$ is the centre of the weld pool, $\theta'$ the arc axis projection, $W$ the width of the weld pool and $\Delta x$ the deviation of the arc axis from the geometrical centre of the weld pool. Xiao\cite{7} reported that mode 2 oscillation occurs when $\Delta x$ is larger than 0.3 mm. In the present study, $\Delta x$ for the partially penetrated welds lies in the range of 0.6 mm to 1.6 mm. In the case of fully penetrated welds $\Delta x$ varies in the range of 2.2 mm to 2.4 mm.

![Figure 3.6 Schematic illustration of arc position with respect to the weld pool.](image-url)
The oscillation frequency of the weld pools were extracted from the high-speed video images. The results are compared with the oscillation frequencies of mode 2 for partially penetrated and mode 2f for fully penetrated weld pools, calculated using equations (2.6) and (2.17) respectively. The calculations were made considering a circular weld pool with an area equal to the weld produced. In the case of partial penetration, the average ratio of weld pool width to length on the top surface $W_t/L_t$ is 0.87 so that $k = 3.744(D/2)^{-1}$. In the case of full penetration, the average $W_t/L_t$ is 0.65 so that $k = 3.515(D/2)^{-1}$, and the average ratio of width on the bottom to width on the top $W_b/W_t$ is 0.65. The surface tension and the density of the material are given in table 3.3.

Table 3.3 Material properties of AISI 316L used in the calculations.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface tension</td>
<td>$1.35 \text{ N m}^{-1}$</td>
</tr>
<tr>
<td>Density</td>
<td>$8000 \text{ kg m}^{-3}$</td>
</tr>
</tbody>
</table>

The oscillation frequencies obtained from the high-speed video analysis and the calculations are presented in figure 3.7a as a function of the weld top width. In this figure the calculations were carried out taking $D$ in the calculations as the equivalent diameter. The figure shows clearly that the oscillation frequency decreases with increasing pool width. For partial penetration pools (mode 2), frequencies in the range of 43 Hz to 89 Hz were found from the high-speed video analysis. For full penetration pools, these frequencies are in the range of 27 Hz to 37 Hz. The transition from partial penetration to full penetration is not accompanied by a steep reduction in oscillation frequency. The calculation results show that at a width of approximately 6.5 mm the frequency of the partially penetrated pool matches that of the fully penetrated pool. This explains the small frequency difference when the weld pool changes its penetration state as observed in the experiments. The calculated oscillation frequencies, however, are higher than those revealed from the experiments. For partial penetration, the oscillation frequencies are in the range of 75 Hz to 142 Hz. For full penetration pools, the frequencies are in the range of 55 Hz to 70 Hz. Most probably the surface tension of the material used in the experiments is lower than that used for calculations. In addition, the use of an equivalent diameter in the calculations may overestimate the oscillation frequency. When $D$ in the calculation is taken as the length of the weld top surface rather than the equivalent diameter, the calculated frequencies are in good agreement with the measured results as shown in figure 3.7b.
Figure 3.7 Weld pool oscillation frequency obtained from the high-speed video analysis (△ partial penetration and ▲ full penetration) and from calculations (— partial penetration and —— full penetration) for autogenous GTA welding; plotted as a function of a) the weld width and b) the weld pool length.
Voltage signals analysis

Figure 3.8 shows the voltage signals during autogenous GTA welding in both partial and full penetration conditions. The base current in the case of partial penetration was 42 A, whilst in the case of full penetration this was 57 A. During the trigger pulse the voltage increases significantly, reaching a value of approximately 40 V. When the current is switched back to the base level, weld pool oscillation is initiated, which causes arc length variation accompanied by voltage oscillation. The observed relationship between arc length and arc voltage is consistent with the description given in chapter 2. Figure 3.8 also shows that the frequency of voltage oscillations in the case of partial penetration is higher than that in the case of full penetration. However, the amplitude of the voltage variation under full penetration conditions is larger. This is probably due to a larger amount of liquid metal present in the weld pool and to the larger freedom of movement in the full penetration case.

Figure 3.8  Voltage signal during oscillation of a) a partially and b) a fully penetrated weld pool in the case of autogenous GTA welding.

Frequency spectra corresponding to the voltage variation shown in figures 3.8a and b are presented in figures 3.9a and b respectively. The spectra, which show the weld pool oscillation frequencies, were revealed by applying FFT analysis as described in section 3.2. An oscillation frequency of 70 Hz is obtained in the case of partial penetration. For the full penetration weld pool the oscillation frequency was found to be 31 Hz.
Figure 3.9 Frequency spectra corresponding to the voltage signals of a) the partially and b) the fully penetrated weld pool in the case of autogenous GTA welding presented in figure 3.8.

Figure 3.10 shows the oscillation frequencies obtained from FFT analyses of the voltage signals and those from high-speed video analyses for autogenous GTA welding. The straight line in this figure represents the condition where the results of both frequency analyses match. It can be seen that the oscillation frequencies are in good agreement. These results support the principle of measuring weld pool oscillation frequency from electrical signals, which is based on the arc length variation and the relationship between arc length and arc voltage. As expected the frequency of the partially penetrated weld pool is higher than that of the fully penetrated weld pool.
3.3.2 Cold-wire GTA welding

Cold-wire GTA welding experiments were carried out to obtain information about the influence of filler wire addition on the weld pool geometry. The heat input was varied by adjusting the base current while other parameters were kept constant (see table 3.2). In this way both partially and fully penetrated weld pools were created. The wire was positioned such that during welding, metal transfer took place in the uninterrupted mode (see section 2.1.1). The weld geometry was compared to the geometry of autogenous GTA welds.

Figures 3.11 and 3.12 show the top views and transverse cross-sections of autogenous and cold-wire GTA welds in the case of partial and full penetration respectively. It can be seen that the shape of the cross-sections is significantly affected by the different conditions. Apparently, the addition of filler wire promotes a deeper penetration.
As described in chapter 2, the weld penetration is strongly influenced by the convection in the weld pool, which is driven by the electromagnetic force, the drag force caused by passage of plasma over the weld pool surface, the buoyancy force and the Marangoni force. Since the welding parameters of cold-wire GTA welding are similar to those of autogenous GTA welding, the
electromagnetic force and the drag force are considered to be similar for both welding processes. In addition, for low-current welding (i.e., below 200 A) the role of the drag force can be neglected. Assuming that the temperature of the droplet in the case of cold-wire GTA welding is comparable to the temperature of the weld pool at the leading edge, the influence of the buoyancy force due to additional liquid metal at the front of the weld pool on the penetration may also be considered negligible. It appears that the penetration increase when filler wire is added is primarily caused by the change in the direction of the Marangoni flow in the weld pool.

Generally speaking, the surface tension depends on both the temperature and the chemical composition, i.e., the concentration of the surface-active elements in particular sulphur and oxygen. According to Mills et al., when the concentration of sulphur is 40 ppm or higher, the temperature coefficient of the surface tension \(d\gamma/dT\) is positive, which produces a radially inward flow and promotes a deep weld penetration. When the sulphur content is lower than 40 ppm, \(d\gamma/dT\) is negative so that an outward flow is produced, which promotes a shallow weld penetration. Analysis of sulphur and oxygen content of the tube and the welding wire by means of infrared adsorption using Leco CS444 and Leco TC436AR equipment are presented in table 3.4. The concentrations of sulphur and oxygen in the filler wire are higher than those in the base material. Due to the addition of the filler wire, the temperature coefficient of the surface tension \(d\gamma/dT\) is altered. As a result, inward flow in the cold-wire GTA welds becomes dominant, increasing the depth of penetration as schematically shown in figure 3.13.

Table 3.4  Sulphur and oxygen content of the tube and wire in ppm.

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI316</td>
<td>&lt;10</td>
<td>20</td>
</tr>
<tr>
<td>ER316LSi</td>
<td>150</td>
<td>60</td>
</tr>
</tbody>
</table>

Figure 3.13 Schematic of a) outward liquid flow in the autogenous GTA weld pool and b) inward flow in the cold-wire GTA weld pool.
When a filler wire, with higher levels of surface active elements, is added at the leading edge of the weld pool, concentration gradient of these elements can be expected. This may cause a more complex flow in the weld pool. Zhao et al.\cite{11} reported that depending upon the concentration of the surface active element, one, two or three vortices with different positions, strength, and directions may be found in the weld pool.

The influence of the base current on the width of the weld top surface is shown in figure 3.14. Solid symbols indicate at which base current full penetration occurs. The figure shows that the width increases with the base current (i.e. heat input). The figure also shows that in the case of cold-wire GTA welding full penetration is reached at a lower base current with a smaller top width in comparison to autogenous welding.

Figure 3.14 Weld top width as a function of the base current for autogenous GTA welding (\(\Delta\)) and uninterrupted cold-wire GTA welding (\(\Theta\)). Open and filled symbols indicate partially and fully penetrated welds respectively.
3.3.3 Uninterrupted cold-wire GTA welding

This section deals with observations of the weld pool during cold-wire GTA welding with uninterrupted metal transfer where the liquid metal flows smoothly into the weld pool (see section 2.1.1). The oscillations of both partially and fully penetrated weld pools were considered. The frequency of the weld pool oscillations was extracted from the high-speed video images and the voltage signals. The results are compared with the results obtained in the case of autogenous welding experiments.

High-speed video observations

A set of high-speed video pictures when partial penetration was obtained \((I_b = 42 \, \text{A})\) is presented in figure 3.15. The figure reveals the dynamics of the weld pool after the current is switched back to the base level. It appears that the weld pool oscillates in mode 2. The occurrence of this oscillation mode can be noted from the position of the crest, which moves from the back of the weld pool \((t = 12352.0 \, \text{ms and 12363.0 ms})\) to the front \((t = 12357.5 \, \text{ms and} \, 12369.5 \, \text{ms})\). The average frequency of the weld pool oscillation in this example was approximately 80 Hz.

![High-speed video observations](image)

Figure 3.15 Oscillations of a partially penetrated weld pool in the case of uninterrupted cold-wire GTA welding.
When the base current was increased, full penetration was obtained. In this situation the weld pool oscillated also in a sloshy mode. The occurrence of this mode, for welding with a base current of 54 A is depicted in figure 3.16. The sloshy motion can be seen by the formation of the crest at the rear ($t = 11714.5$ ms, $11742.0$ ms and $11764.0$ ms) and at the front ($t = 11728.0$ ms, $11750.5$ ms) of the weld pool. The average frequency of the weld pool oscillation revealed from the high-speed images in this example was 43 Hz.

![Figure 3.16 Oscillations of a fully penetrated weld pool in the case of uninterrupted cold-wire GTA welding.](image)

As in the autogenous GTA welding case, the occurrence of a sloshy oscillation in the partially and fully penetrated pools during cold-wire GTA welding is believed to be caused by the deviation of the arc axis from the centre of the weld pool. The value of $\Delta x$ in the case of cold-wire welding is in the range of 1.2 mm to 1.4 mm for partial penetration and in the range of 2.8 mm to 3.4 mm for full penetration.

The oscillation frequencies obtained from the high-speed video analysis and those from calculations for uninterrupted cold-wire GTA welding are presented in figure 3.17. The frequencies are plotted as a function of the weld top width (figure 3.17a) and the weld pool length (figure 3.17b). The calculations were carried out using a similar approach and material properties as those used for autogenous welding (refer to section 3.3.1 and table 3.3). It is shown in figure 3.17a that in the case of partially penetrated pools, oscillation
frequencies in the range of 80 Hz to 105 Hz were found from the analysis of the high-speed video images and in the range of 120 Hz to 148 Hz from the calculations. For full penetration pools the oscillation frequencies are in the range of 28 Hz to 60 Hz and in the range of 52 Hz to 76 Hz respectively. Similar to the case of autogenous GTA welding, the transition from the partial penetration condition to the full penetration condition is not marked by any abrupt change in the oscillation frequency. Additionally, a better match between the calculations and the measurements is obtained if the weld pool length rather than the equivalent diameter is used in the calculation (see figure 3.17b).

It should be noted that the penetration transition in the case of uninterrupted cold-wire GTA welding occurs at a smaller pool size and thus a higher oscillation frequency than in the case of autogenous GTA welding. This is caused by the influence of the filler wire on the weld penetration; the temperature coefficient of the surface tension \( \frac{d\gamma}{dT} \) will change in such a way that an inward directed flow in the weld pool is generated. Nevertheless the oscillation frequencies of both partial and full penetration weld pools of the same width are about equal for both welding processes (compare figure 3.7 with figure 3.17).
Figure 3.17 Weld pool oscillation frequency from high speed video analysis (○ partial penetration and ● full penetration) and from calculations (— partial penetration and —— full penetration) for cold-wire GTA welding in an uninterrupted transfer mode; plotted as a function of a) the weld width and b) the weld pool length.
Voltage signals analysis

In the case of uninterrupted metal transfer, the voltage response to the trigger pulse for a partially penetrated weld pool is presented in figure 3.18a. In this example the weld was produced with a base current of 42 A. In figure 3.18b, the voltage signal of a fully penetrated weld is shown. The weld was produced with a base current of 54 A. In both cases an oscillation of the voltage signals can be seen after the trigger pulse. When the voltage signals are related to the visual observations it appears that a low voltage coincides with a small arc length, as was also observed in the case of autogenous GTA welding.

![Figure 3.18 Voltage signal during oscillation of a) a partially and b) a fully penetrated weld pool in the case of uninterrupted cold-wire GTA welding.](image)

When FFT analysis is applied to the voltage signals, frequency spectra as shown in figures 3.19a and b are obtained. The figures show that the oscillation frequency of the partially penetrated pool (94 Hz) is higher than that of the fully penetrated weld pool (47 Hz).

The oscillation frequencies obtained from the FFT analysis of the voltage signals are in agreement with those obtained from the analysis of high-speed video images, over a wide range of weld pool size. This agreement is shown in figure 3.20. This implies that when the molten wire transfers smoothly to the weld pool there is no significant influence of the metal transfer on the voltage signal.
Figure 3.19 Frequency spectra corresponding to voltage signals of a) the partially and b) the fully penetrated weld pool in the case of uninterrupted cold-wire GTA welding presented in figure 3.18.

Figure 3.20 Comparison between weld pool oscillation frequencies obtained from the FFT analysis of voltage signals and from the high-speed video analysis for uninterrupted cold-wire GTA welding (○ partial penetration and ● full penetration).
3.3.4 Interrupted cold-wire GTA Welding

High-speed video observations

In the interrupted mode, the metal transfer occurs by interrupted contact between the weld pool and the melted wire (see section 2.1.1). To obtain information about the behaviour of the weld pool and the droplet in this transfer mode, high-speed imaging was used.

In the case of partial penetration, the current pulse triggers the weld pool in a mode 2 oscillation. The pendant droplet does not affect this motion. This can be seen in figure 3.21, which shows a weld pool and a droplet during welding with a base current of 42 A. A sloshy mode can be seen from $t = 2441.0$ ms to $2452.0$ ms, with an oscillation frequency of approximately 90 Hz. The weld pool is also triggered into a sloshy oscillation due to the transfer of the metal droplet. This phenomenon can be seen in figure 3.22, where contact between the droplet and the workpiece occurs at $t = 2764.0$ ms and the transfer of the liquid metal at 2776.5 ms. When the metal transfer is completed the weld pool oscillation starts ($t = 2781.5$ ms). The frequency of the sloshy oscillation mode is approximately 85 Hz. Both types of triggering, i.e. by the current pulse and by droplet transfer, result in similar oscillation frequencies of the weld pool. In the case of full penetration, similar phenomena are observed. In a welding experiment with a base current of 48 A for instance, the weld pool was triggered into a sloshy oscillation mode. When the weld pool was triggered by a current pulse the weld pool oscillation frequency was found to be 53 Hz. Occasionally, the transferring droplet triggered the weld pool oscillation, which resulted in a frequency of 52 Hz.

It was also observed that the pendant metal droplet in the case of interrupted bridging transfer oscillates independent of the state of the weld penetration. In figure 3.21 it can be seen that due to the current pulse, the pendant droplet is pushed away from the electrode, and the droplet starts to oscillate. The motion of the pendant droplet seems to affect the geometry of the arc. It can be expected that the change in the arc geometry will influence the electrical signals (voltage). From the high-speed video images the droplet oscillation frequency can be determined. At $t = 2438.0$ ms and 2480.0 ms the droplet is closest to the electrode whilst at $t = 2458.5$ ms and 2499.0 ms the droplet is at its maximum distance from the electrode. This gives an oscillation frequency of approximately 25 Hz. As the droplet grows, the droplet oscillation frequency gradually decreases.
Figure 3.21 Weld pool oscillation, droplet oscillation and droplet detachment during interrupted cold-wire GTA welding in the case of partial penetration.

Figure 3.22 Weld pool oscillation triggered by droplet transfer during interrupted cold-wire GTA welding in the case of partial penetration.
Voltage signals analysis

It was observed from the high-speed video images that during interrupted cold-wire GTA welding, besides weld pool oscillation due to the trigger current, two other phenomena, pendant droplet oscillation and weld pool oscillation due to metal transfer occur. The transfer of the liquid filler metal to the weld pool takes place after a number of trigger pulses. During these pulse cycles, a droplet is formed at the tip of the filler wire and grows to a considerable size. After contacting the weld pool, the liquid metal of the droplet is transferred. In order to distinguish the influence of the different phenomena on the voltage signals, FFT analyses were carried out. Furthermore, the voltage data was compared to the high-speed video pictures.

Typical voltage signals of interrupted cold-wire GTA welding under partial penetration conditions are presented in figure 3.23, which shows the voltage as a function of time for three different trigger pulses (numbered from 1 to 3). The shaded regions in figure 3.23 indicate the regions used for FFT analysis. The voltage data in region A are used for FFT analyses to obtain information on the frequency of weld pool oscillation triggered by the pulse current. The voltage data in region B are used to obtain information on the frequency of the weld pool and droplet oscillations before the subsequent current pulse. The results of FFT analyses are presented in figure 3.24.

It can be seen that the frequency of the voltage in line 3 is significantly lower than that in line 1 even though there is no change in the weld pool size. FFT analysis applied on the data of line 1A reveals a frequency peak of 94 Hz (see figure 3.24a). During this period the pendant droplet is very small. The frequency can therefore be related to the weld pool oscillation initiated by the trigger pulse. This frequency correlates well with the frequency obtained from the high-speed video analysis.
Figure 3.23 Voltage signals for three trigger pulse cycles during interrupted cold-wire GTA welding in partial penetration condition.

Figure 3.24 Frequency spectra corresponding to voltage signals of a) line 1A, b) line 2A, c) line 3A and d) line 3B as presented in figure 3.23.
When the same FFT procedure is used on line 2A, two frequency peaks at about 39 Hz and 100 Hz are revealed (see figure 3.24b). Visual observations confirm that the frequency of 39 Hz can be associated with the droplet oscillation, whilst the frequency of 100 Hz is related to the weld pool oscillation triggered by the arc force. Note that droplet oscillation at the wire tip can be detected from the voltage signals after the droplet has grown to a considerable size. The relationship between the voltage variation and the droplet oscillation is due to the periodic change of arc column shape and effective arc length. The high-speed video pictures show a periodic motion of the droplet out of and into the arc plasma (see figure 3.21). When the droplet is closest to the electrode axis, the voltage reaches its peak value and the arc column diameter reduces. In addition, the arc is slightly deflected and the effective arc length increases.

Line 3 in figure 3.23 represents the condition shown by high-speed video pictures in figures 3.21 and 3.22. The FFT analysis of line 3A reveals a dominant low oscillation frequency of 23 Hz (figure 3.24c), which is related to the oscillation of the pendant droplet (see figure 3.21). This frequency is slightly lower than the low frequency obtained in line 2A, since the droplet has become even larger and the droplet oscillation frequency gradually decreases with increasing size. The high frequency peak, observed earlier in line 2A, has disappeared. Apparently, the influence of the droplet oscillation on the arc voltage overrules the influence of voltage variation due to weld pool oscillation.

Finally, in the latter part of line 3 (see line 3B in figure 3.23) droplet transfer takes place. One can see a voltage drop of about 0.9 V, approximately 300 ms after the trigger pulse (indicated by the arrow in figure 3.23). The high speed video pictures show that at this moment the first contact between the pendant droplet and the weld pool is established. This is accompanied by a change in the direction of the arc (see at $t = 2499.0$ ms in figure 3.21 and at $t = 2764.0$ ms in figure 3.22). The high-speed video pictures also show that 36 ms after this voltage drop the droplet is completely detached and the weld pool starts oscillating. As can be seen in figure 3.22, due to the droplet transfer, the weld pool is triggered into oscillation mode 2. The picture also shows that after the droplet detachment the amount of the remaining liquid at the filler wire tip is very small. The weld pool oscillation is reflected by the voltage oscillation. At the same time the average voltage remains low as the transferred liquid metal is situated underneath the arc, keeping the arc length small. If FFT analysis is applied on line 3B (256 data points up to 10 ms before the subsequent trigger pulse), it reveals a peak frequency of 86 Hz (see figure
This frequency can be related to the weld pool oscillation triggered by the transferred droplet.

Experiments were also carried out in the case of fully penetrated weld pools and similar phenomena, i.e. the oscillation of the weld pool due to the current pulse and the droplet transfer as well as the oscillation of the pendant droplet, were observed. In figure 3.25 the voltage data for three pulse cycles is presented for interrupted cold-wire GTA welding when full penetration is achieved. Again, the shaded regions in the figure indicate the regions for FFT analysis. The results of the FFT analysis of these signals are presented in figure 3.26.

The voltage signals displayed as line 1 in figure 3.25 represent the situation when the pendant droplet is small and the weld pool oscillation dominates the variation of the arc voltage. A frequency of 55 Hz was obtained from FFT analysis of line 1A (see figure 3.26a). This frequency is reduced compared to the partial penetration condition (figure 3.24a) due to the larger weld pool size in combination with the change of the oscillation mode.

In the subsequent pulse cycle (line 2), the droplet has grown. An FFT analysis of line 2A reveals a frequency spectrum presented in figure 3.26b. The figure shows a dominant frequency of 55 Hz, which can be associated with weld pool oscillation and a second frequency peak of 23 Hz, which is related to the pendant droplet oscillation.

In the case of line 3A in figure 3.25, the FFT analysis again reveals a frequency peak of 55 Hz (see figure 3.26c). Observations by means of high-speed video show that this frequency is related to the oscillation of the weld pool. It is also observed that the oscillation of the pendant droplet becomes erratic, which can be caused by lack of synchronisation between the current pulse and the movement of the pendant droplet. This could lead to the damping of the droplet oscillation. It should be noted that the erratic motion of the droplet is not related to the penetration state of the weld pool.

In the latter part of line 3 (line 3B), triggering of the weld pool by means of droplet transfer takes place as was also the case in the partial penetration. FFT analysis reveals that the weld pool oscillates at a frequency of 39 Hz.
Figure 3.25 Voltage signals for three successive trigger pulse cycles during interrupted cold-wire GTA welding in full penetration condition.

Figure 3.26 Frequency spectra corresponding to voltage signals of a) line 1A, b) line 2A, c) line 3A and d) line 3B as presented in figure 3.25.
3.3.5 Influence of filler wire addition on the weld pool oscillations frequency

It has been shown in the previous sections that the calculated weld pool oscillation frequencies are in better agreement with the results of the measurement when D in the calculation is taken as the length of the weld top surface rather than the equivalent diameter. The error of calculated frequency relative to the measured frequency (based on the high speed video) are summarised in table 3.5.

The calculated frequencies better match the results of the measurement in the case of full penetration weld pools than in the case of partial penetration. The reason for this it is not fully understood; however, this could be caused by differences in the surface tension. The surface tension is averaged for the prediction, whereas it is highly non-uniform across the pool surface in reality. Also the model takes no account of convection in the weld pool (which will differ between partial and full penetration cases, nor does it take account of surface depression due to the presence of the arc. One further difference between full and partial penetration is that full penetration involves the average surface tension over two free surfaces (one directly heated the other not), whilst for partial penetration only the upper (heated) surface contributes. This could give rise to significant differences between the partial and full penetration states. Calculation of the weld pool oscillation frequency based on pool length rather than equivalent diameter appears justified, at least in the case of the full penetration sloshy mode. The addition of filler wire increases oscillation frequency in the partial penetration mode, but has little influence on the oscillation frequency of fully penetrated weld pools. The addition of filler wire may influence the temperature coefficient \( \frac{d\gamma}{dT} \). The effect on the average value of the surface tension is however uncertain.

Table 3.5  Summary of weld pool oscillation frequencies.

<table>
<thead>
<tr>
<th>Welding condition</th>
<th>Penetration</th>
<th>Oscillation Frequency Range from the high-speed video (Hz)</th>
<th>Average error of calculated frequency relative to the measured frequency (Hz)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Using ( D_{eq} )</td>
<td>Using ( L_t )</td>
</tr>
<tr>
<td>Autogenous</td>
<td>Partial</td>
<td>43-89</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>27-37</td>
<td>31</td>
</tr>
<tr>
<td>Uninterrupted</td>
<td>Partial</td>
<td>80-105</td>
<td>42</td>
</tr>
<tr>
<td>cold-wire</td>
<td>Full</td>
<td>28-60</td>
<td>25</td>
</tr>
<tr>
<td>Interrupted</td>
<td>partial</td>
<td>85-90</td>
<td>45</td>
</tr>
<tr>
<td>cold-wire</td>
<td>Full</td>
<td>52-53</td>
<td>23</td>
</tr>
</tbody>
</table>
3.5 Conclusions

On the basis of the experimental results obtained, the following conclusions can be drawn.

- The penetration of cold-wire GTA welds may differ from that of autogenous welds due to the change in the chemical composition of the weld pool. As a result the transition from the partial to the full penetration in cold-wire GTA welding can take place at a different pool size from that in autogenous GTA welding.

- Under welding conditions used in this work, the oscillatory behaviour of the uninterrupted cold-wire GTA weld pool is similar to that observed in the case of autogenous welding. In both partial penetration and full penetration cases the weld pool oscillates in a sloshy mode. At a similar pool size the oscillation frequency of cold-wire GTA weld pools is comparable to that of the autogenous GTA weld pools. The transition from partial to full penetration is accompanied by only a small drop in frequency.

- The oscillation frequency measured from the voltage signals is in a good agreement with that obtained from the high-speed video analysis but lower than that obtained from calculations based on an equivalent weld pool diameter. This may be partially explained by changes in surface tension; however for sloshy mode oscillations, calculations of oscillation frequency taking $D$ as the length of the weld pool top surface provide a much better match to experimental results than those based on an equivalent diameter.

- The uninterrupted metal transfer does not significantly affect the voltage signals.

- The interrupted metal transfer can disturb the voltage signals. In this transfer mode, voltage variations are not only caused by pool oscillation due to current pulses but can also be caused by droplet oscillation and by pool oscillation triggered by the metal transfer. Droplet oscillation at the wire tip can be detected after the droplets grow to a considerable size and the oscillation frequency decreases with increasing droplet size.

- The results obtained in this study imply that weld pool oscillation can be used for penetration sensing and control during cold-wire GTA welding when uninterrupted transfer is maintained.
References

11. Zhao, Y. Z., Shi, Y. W., and Lei, Y. P., The study of surface-active element oxygen on flow patterns and penetration in A-TIG welding,
Chapter 4:
Oscillation based penetration sensing during orbital cold-wire GTA welding

4.1 Introduction

In the previous chapter weld pool oscillation during GTA welding with filler wire addition has been described. It was shown that disturbance of the weld pool oscillation and of the voltage signals due to metal transfer can be avoided if the metal transfer takes place in the uninterrupted mode. This implies that weld pool oscillation can be used for penetration sensing and control during cold-wire GTA welding with similar accuracy to autogenous GTA welding, when uninterrupted transfer can be maintained.

One of the promising applications of oscillation based penetration sensing is in orbital welding.[1-3] Orbital welding is an automated welding process, which was firstly developed in the early 1960s.[4] Nowadays, orbital welding is used routinely for welding pipes in chemical, food processing, pharmaceutical, aerospace and power industry. In orbital welding, the tubes or pipes are kept in a fixed position and the welding torch travels around the tubes or pipes (figure 4.1). As a result, the effect of gravity on the weld pool during orbital welding is variable. The influence of this gravitational force on the weld pool oscillation frequency for tube, however, was reported to be negligible for pipes with a wall thickness of up to 3 mm.[1,5]

In the literature no reference has been found on penetration sensing and control by means of weld pool oscillation monitoring for orbital cold-wire GTA welding. This chapter deals with experiments to demonstrate such a case.
The wire delivery device was positioned in such a way that uninterrupted metal transfer was ensured. For comparison purposes autogenous GTA welding experiments were also carried out. The approach for penetration sensing selected in this work was the so-called single frequency approach. In this approach, a pre-set oscillation frequency is determined as a reference by means of test welds and is used to control the process. This frequency corresponds to a full penetration condition. During welding the measured oscillation frequency is compared with the reference frequency. When the measured frequency and the pre-set reference value are not equal, the feedback system adjusts the welding current. In this way the weld pool size is adjusted and the oscillation frequency approaches the pre-set value. This single frequency approach is also adopted in the work of Hu and den Ouden.\textsuperscript{[1]}

![Figure 4.1](image.png)

Figure 4.1 Schematic illustration of the orbital or PG-PF\textsuperscript{[6]} welding positions. The welding travel directions are indicated by the arrows.

4.2 Experimental conditions

4.2.1 Materials and consumables

Experiments on weld penetration control during cold-wire GTA welding were carried out using material and filler wire similar to those used in the experiments described in the previous chapter (see section 3.2). The shielding gas was a mixture of Ar and 5% H\textsubscript{2} with a flow rate of 10 l min\textsuperscript{-1}, whilst the backing gas was Ar with a flow rate of 4 l min\textsuperscript{-1}. The nominal chemical composition (wt %) of the tubes and the filler wire are given in table 3.1 (see chapter 3).
4.2.2 Welding system

Bead-on-tube welds were made by using ESAB PRC 36-80 orbital welding equipment. This equipment has jaws to clamp the tube (see figure 4.2). During welding, the tube was kept in a horizontal position and the torch rotated. The welding equipment also has a motor to drive the torch up or down perpendicular to the weld pool surface to control the arc length. To produce the welds, a Stel TIG S350 Inverter power source capable of supplying a maximum of 350 A welding current was used in a constant current characteristic mode. A 2% thoriated tungsten electrode was used with a diameter of 2.4 mm and a tip angle of 60°.

Figure 4.2 a) Picture and b) schematic illustration of the orbital welding system (the welding torch moving around a fixed pipe or tube).

The welding process was started from the 12 o’clock position and was stopped when the torch returned to its initial position after rotating 360 degrees. The welding arc was ignited by short-circuiting the electrode and the workpiece using a carbon rod during which the current was set at 20 A. Trigger pulses were produced by sending a square pulse signal to the power source. During welding, the filler wire was continuously fed to the front of the weld pool in such a way that the angle between the wire and the workpiece was approximately 20°. To maintain the contact between the wire and the weld pool so that an uninterrupted metal transfer was obtained, an arc voltage control system was activated resulting in arc length adjustment. Typical welding parameters used in the experiments are presented in table 4.1.
Table 4.1  Welding conditions for autogenous orbital GTA welding.

<table>
<thead>
<tr>
<th>Shielding gas / flow rate</th>
<th>Ar + 5% H\textsubscript{2} / 10 l min\textsuperscript{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backing gas / flow rate</td>
<td>Ar / 4 l min\textsuperscript{-1}</td>
</tr>
<tr>
<td>Arc length</td>
<td>1-2 mm</td>
</tr>
<tr>
<td>Base current</td>
<td>30-60 A</td>
</tr>
<tr>
<td>Trigger current</td>
<td>300 A</td>
</tr>
<tr>
<td>Trigger frequency</td>
<td>2 Hz</td>
</tr>
<tr>
<td>Trigger time</td>
<td>3 ms</td>
</tr>
<tr>
<td>Travel speed</td>
<td>2 mm s\textsuperscript{-1}</td>
</tr>
<tr>
<td>Wire feed rate</td>
<td>5 mm s\textsuperscript{-1}</td>
</tr>
</tbody>
</table>

Labview software and a data acquisition card PCI 1200 from National Instruments were used to operate the welding equipment, to control the arc length and to control the weld penetration with the single frequency approach. Figure 4.3 shows the flow diagram of the computer program. The input parameters are: welding time $t_\text{weld}$, initial base current $I_b(0)$, trigger current $I_t$, trigger duration $t_t$, trigger frequency $f_t$, reference frequency $f_\text{ref}$ and reference voltage $U_\text{ref}$. The reference frequency was selected based on the results presented in chapter 3 (see figure 3.19).

![Flow diagram of penetration sensing and control for the orbital GTA welding experiments.](image)
The data acquisition was carried out to sample voltage and welding current (2 channels) at a sampling rate of 20480 samples per second. Voltage data was processed to obtain the frequency of weld pool oscillation. Before frequency analysis, the DC component was removed and the voltage signals were filtered using a 6th order Butterworth band-pass filter with a cut-off frequency of 20 Hz - 200 Hz, following the procedure described by Barborak. [7] An FFT analysis was carried out over 4096 voltage data points (corresponding to 200 ms), starting approximately 20 ms after the trigger. This analysis yields a frequency resolution of 5 Hz. The measured oscillation frequency $f$ was then compared with the reference frequency $f_{ref}$ and the outcome in combination with the measured base current $I_b$ were used for current feedback. The rate of current adjustment was determined experimentally and was dependent on the difference between the measured oscillation frequency and the reference frequency. Current adjustments, if necessary, were carried out after each trigger cycle.

The arc length was controlled automatically by means of the relationship between arc voltage and arc length. For this purpose, the voltage data measured during the base period were averaged. This average value $U_{(n)}$ was then compared with a preset reference voltage $U_{ref}$. When necessary, the system sent a signal (5 V or -5 V) to the power supply of the motor to adjust the torch position.

### 4.3 Results and discussion

Autogenous and uninterrupted cold-wire GTA welding experiments were carried out to obtain information on the penetration status of the weld produced. Different settings of reference frequency were used to produce partial and full penetration welds. Figure 4.4 shows the state of penetration of the welds obtained during orbital welding with various reference frequencies. The figure demonstrates that for each welding process there is a maximum reference frequency up to which full penetration is guaranteed. Above this value partial penetration welds are obtained. The maximum reference frequency to obtain full penetration for cold-wire GTA welding is 60 Hz, whilst for the autogenous GTA welding this is 40 Hz. Decreasing the reference frequency results in a larger pool width and will ultimately cause severe sagging of the weld pool. The difference in the maximum reference frequency to get full penetration for both welding processes (figure 4.4) appears to be related to the pool size needed to reach full penetration.
Reference frequency (Hz)

<table>
<thead>
<tr>
<th>Welding</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autogenous</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold-wire</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note:  
- : Partial penetration  
- : Full penetration

Figure 4.4 Penetration state during orbital GTA welding of tubes for various reference frequencies.

In figure 4.5, the average widths of the weld top surface, which were obtained by averaging the width of welds measured at 12 positions from 1 o’clock to 12 o’clock, are presented as a function of the reference frequency. Figure 4.5 shows an average width of 6.2 mm for the autogenous GTA weld with a 40 Hz reference frequency, and an average width of 5.3 mm for the cold-wire GTA weld with a reference frequency of 60 Hz.

Figure 4.5 Average weld top width as a function of the reference frequency for autogenous GTA welding (Δ) and uninterrupted cold-wire GTA welding (O). Open and filled marks indicate partially and fully penetrated welds respectively.
The results shown in figures 4.4 and 4.5 agree with those presented earlier in chapter 3, which indicate that the addition of the filler wire influences the pool geometry. Presumably, the filler wire addition modifies the chemical composition of the weld metal, leading to the formation of an inward weld pool flow and the production of a deeper weld penetration. As expected, the base current required for fully penetrated welds during cold-wire GTA welding is lower than that for autogenous welding, as shown in figure 4.6.

In figures 4.7 and 4.8 plots of the welding current and the oscillation frequency are presented as a function of welding position for orbital autogenous and orbital cold-wire GTA welding respectively. The reference frequencies used to produce these welds were 40 Hz for autogenous welding and 60 Hz for cold-wire welding (indicated by the solid lines in the figures). Visual observation during cold-wire GTA welding showed that the metal transfer took place in the uninterrupted mode.

It can be seen in figure 4.7 that when the oscillation frequency is higher than the reference frequency, the welding base current increases, broadening the weld pool and ensuring full penetration. As a result the oscillation frequency
reduces. When the oscillation frequency further reduces and becomes lower than the reference frequency, the welding current reduces to increase the oscillation frequency by decreasing the pool size. It should be noted that a high oscillation frequency (>100 Hz) was observed during the first few seconds of autogenous welding (see figure 4.7). It appears that in this situation, the weld pool oscillates in mode 1. The occurrence of this mode can be expected since during this first few seconds the weld pool is small in size, has a relatively round shape and even though it is fully penetrated, the weld bottom width did not reach half of the weld top width. This is a requirement mentioned by Xiao\textsuperscript{[8]} to obtain a mode 3 oscillation related to full penetration. Since the electrode is situated above the weld pool centre, the liquid metal oscillates in an axisymmetric mode. At the end of the weld, the current drops slightly, which could be caused by the accumulation of heat in the tube. As the arc travels towards the warmer region, less heat is required to maintain full penetration. These results were also mentioned by Aendenroomer\textsuperscript{[5]} as well as Hu and den Ouden.\textsuperscript{[1]}

![Figure 4.7](image)

**Figure 4.7** Plots of welding current (○), oscillation frequency (—) and reference frequency (…..) as a function of welding position during autogenous GTA welding with penetration sensing when full penetration was successfully maintained along the weld. The reference frequency was 40 Hz.

The response of the welding base current to the control system in the case of cold-wire GTA welding can be seen clearly in figure 4.8. Similar to the case
of autogenous welding, the welding base current increases when the oscillation frequency is higher than the reference frequency. As a result the weld pool broadens and the oscillation frequency decreases. When the oscillation frequency is lower than the reference frequency, the welding base current decreases. As a response to the decreasing base current, the weld pool becomes smaller and the oscillation frequency increases.

Figure 4.8 Plots of welding current (○), oscillation frequency (—) and reference frequency (-----) as a function of welding position during orbital cold-wire GTA welding with penetration sensing when full penetration was successfully maintained along the weld with a reference frequency of 60 Hz.

In figure 4.9 plots of the welding current, the oscillation frequency and the reference frequency (40 Hz) are presented as a function of welding position for orbital cold-wire GTA welding. A lower reference frequency indicates a larger weld pool, which requires a higher welding current. In comparison with figure 4.8, figure 4.9 shows that when a lower reference frequency is used (40Hz), reduction of current variation is observed. For a wider weld pool, changes in weld pool width will result in minor changes of the oscillation frequency and therefore, this hardly affects the welding current.
Figure 4.9 Plots of welding current (○), oscillation frequency (—) and reference frequency (-----) as a function of welding position during orbital cold-wire GTA welding when full penetration was successfully maintained along the weld with a reference frequency of 40 Hz.

4.4 Conclusions

In this chapter the results of experiments with orbital cold-wire GTA welding using oscillation based penetration sensing have been presented and discussed. The following conclusions can be drawn:

- The possibility to use oscillation based penetration sensing to maintain full penetration in cold-wire GTA welding has been demonstrated. A successful application of such a system can be obtained when the metal transfer takes place in an uninterrupted mode.
- The slight current drop observed at the end of the weld, when the penetration sensing is applied, is due to heat accumulation in the tube. As the arc travels towards the warmer region, less heat is required to maintain full penetration.
- The addition of filler wire can change the weld pool geometry. Presumably, this is caused by the modification of the weld chemical composition. The implication in this case is that for welding different materials and/or filler wires using the single frequency approach, welding trials are required to determine an appropriate reference frequency.
References

Chapter 5:
Liquid metal and arc behaviour during pulsed-current GMA welding

5.1 Introduction

In chapter 3 the study of liquid metal oscillation during GTA welding with filler wire addition has been presented. It was shown that weld pool oscillation frequency could be determined from the voltage signals with similar accuracy to that found for the case of autogenous GTA welding. Moreover, the possibility to use weld pool oscillation for penetration sensing during GTA welding with filler wire addition was demonstrated, as presented in chapter 4. Since the productivity of GMA welding is higher in comparison to GTA, the possibility to automatically control penetration during GMA welding will significantly benefit manufacturing industry. In an attempt to extend the application of penetration sensing and control based on weld pool oscillation to GMA welding, insight into the weld pool behaviour of this welding process is required. In addition, a practical approach to monitor weld pool oscillation frequency in this dynamic process is needed.

In the past, investigations of the weld pool oscillation phenomenon during GMA welding were focused on short-circuiting GMA (S-GMA). As described in chapter 2, S-GMA welding is a highly dynamic process in which the electrode wire periodically contacts the weld pool. During this short-circuit period the welding current increases. As a result, the electromagnetic pinch force increases and finally breaks the liquid bridge. Simultaneously, the arc is re-ignited and the high arc pressure triggers the weld pool into oscillation. Monitoring of weld pool oscillation in short-circuiting GMA welding however is problematic, since the short-circuit disturbs both the weld pool oscillation and the voltage.
To avoid the disturbance of short-circuiting on the voltage signals, GMA welding can be performed under open arc conditions. In conventional GMA welding, the metal transfer under open arc conditions can take place in a spray mode or in a globular mode depending on the current level. The spray mode takes place at a relatively high welding current. In this transfer mode the size of the droplet is approximately equal to or smaller than the electrode diameter and droplets are detached due to the pinch force at the electrode tip. As a result of the constant high current, a high arc pressure depresses the weld pool continuously, which hampers weld pool oscillation. The globular mode is characterised by the transfer of large droplets across the arc (the diameter of the droplet is larger than the diameter of the wire). The droplets are detached from the wire primarily due to the action of gravity. This transfer mode can be unstable since the arc can become erratic and the droplet can be repelled by the arc pressure.

As described in chapter 2, to maintain the advantage of spray transfer, i.e. the directional metal transfer and stability, while reducing the heat input, pulsed-current GMA (P-GMA) welding can be used. In this process metal transfer can be controlled in such a way that one droplet is detached per pulse. This condition can be obtained by selecting appropriate welding parameters. The possibility to control droplet detachment gives an opportunity to adjust the time interval between pulses, and thus the time for monitoring liquid metal oscillation, over a wide range. With this advantage, P-GMA welding is considered to be the most appropriate process variant to study weld pool oscillation in consumable arc welding.

The P-GMA process was observed using a high-speed video camera. The possibility to monitor the oscillation frequency from the voltage signals was also investigated. In GMA welding the consumable electrode melts due to the heat of the arc and the effect of joule heating. As a result, a liquid droplet is formed at the end of the electrode. The pendant droplet and the weld pool are part of the electrical circuit and contribute to the measured voltage. The behaviour of these liquid bodies may influence the condition of the arc, and hence the voltage. For this reason attempts were made to correlate patterns in the voltage signal with the physical phenomenon observed by high-speed video.
5.2 Experimental procedure

5.2.1 Materials and consumables

Bead-on-plate welds were made on 2 and 6 mm thick S235JR steel plates by P-GMA welding. A 1 mm diameter ER70S6 filler wire was used as the electrode. The chemical composition of the base material and the filler wire are listed in table 5.1. A mixture of Ar + 5% CO₂ was used as a shielding gas, with a flow rate of 10 l min⁻¹.

Table 5.1 Nominal chemical composition wt %(*) of the materials used in the experiments (Fe balance).

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>S235JR[6]</td>
<td>0.17</td>
<td>1.4</td>
<td>0.3</td>
<td>0.045</td>
<td>0.045</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>N 0.009</td>
</tr>
<tr>
<td>ER70S-6[7]</td>
<td>0.06-0.15</td>
<td>1.40-1.85</td>
<td>0.80-1.15</td>
<td>0.025</td>
<td>0.035</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.03</td>
<td>Cu 0.5</td>
</tr>
</tbody>
</table>

(*) Single values are maximum values.

5.2.2 Welding system and parameters

Figure 5.1 schematically shows the experimental arrangement. A MacGregor power source capable of supplying a maximum 500 A welding current was used to make the welds in a positive electrode (wire) polarity and a constant current power source characteristic. In all cases the electrode was placed perpendicular to the workpiece and the welds were made in the flat PA position. The contact tip to workpiece distance (CTWD) was 20 mm.

Preliminary experiments were carried out to determine welding parameters that give a stable open arc situation (without short-circuiting) with pulse frequencies of 53 and 32 Hz. The frequency of 53 Hz was selected since it represents the low frequency range commonly used in practice. The frequency of 32 Hz was selected because this enables an even longer observation period between two subsequent pulses yet still gives a stable process condition.[8] In the preliminary experiments, the base current, peak current, pulse time and travel speed were kept constant at 58 A, 290 A, 3 ms and 5 mm s⁻¹. The wire feed rate was varied to change the arc length. The results of these experiments are
presented in figure 5.2, which shows the average voltage as a function of wire feed rate. It can be seen that the average voltage drops with increasing wire feed rate due to the reduction of the arc length. When the arc becomes too short, short-circuiting occurs as indicated by the open symbols in the figure. Welding conditions were selected that give an almost constant arc length, with an average voltage of approximately 22 V.

The main experiments were carried out using the welding parameters given in table 5.2. With a peak current of 290 A a one-drop-per-pulse situation was obtained. In the experiment with a pulse frequency of 53 Hz, a larger droplet size was produced by lowering the peak current to 230 A. With this peak current, in general, several pulses are required to detach a droplet. To produce different weld pool sizes on both partial and full penetration cases, the travel speed during the experiment with a pulse frequency of 32 Hz was varied.
Figure 5.2  Average voltage as a function of wire feed rate during welding for \( f_p = 53 \text{ Hz} \) (●) and 32 Hz (▲). The open symbols indicate short-circuiting conditions.

Table 5.2  Welding conditions.

<table>
<thead>
<tr>
<th>Penetration*</th>
<th>Partial</th>
<th>Full</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse frequency ( f_p )</td>
<td>53 Hz</td>
<td>32 Hz</td>
</tr>
<tr>
<td>Base current ( I_b )</td>
<td>58 A</td>
<td>58 A</td>
</tr>
<tr>
<td>Peak current ( I_p )</td>
<td>230 and 290 A</td>
<td>290 A</td>
</tr>
<tr>
<td>Peak time ( t_p )</td>
<td>3 ms</td>
<td>3 ms</td>
</tr>
<tr>
<td>Travel speed ( v )</td>
<td>5 mm s(^{-1})</td>
<td>3, 5 and 7 mm s(^{-1})</td>
</tr>
<tr>
<td>Wire feed rate ( WFR )</td>
<td>53 and 65 mm s(^{-1})</td>
<td>49 mm s(^{-1})</td>
</tr>
</tbody>
</table>

*) Note: The partially penetrated welds were produced on 6 mm thick plates, whilst the fully penetrated welds were produced on 2 mm thick plates.

5.2.3 High-speed imaging system and image analysis

A high-speed imaging system as described in chapter 3 was used in this study. Two halogen lamps each of 1000 W were used to illuminate the field of interest. Capturing of the video images was synchronised with the electrical signal monitoring. Typically an imaging frame rate of 2000 Hz was used. The oscillatory behaviour of the droplet was analysed by correlating the droplet size to the droplet oscillation frequency. Measurements of the pendant and the free
falling droplet size were carried out using Autocad software and sizes were assigned based on an equivalent spherical volume.

Direct information about the weld pool oscillation from the high-speed video pictures was obtained by tracing the pool surface as a function of time. For this purpose a number of reference points were defined as depicted in figure 5.3 (points A to G). The inter-distance between the reference points defined by \( a \) is equal to the distance between the electrode axis and the weld pool leading edge. The reference point \( D \) is situated at the centre of the weld pool. The distances between the reference points and the original plate surface (\( h_A \) to \( h_G \)) were measured as a function of time. In this way the change of the position of each reference point during welding can be outlined and the trend of the pool dynamics can be revealed. The image analysis was carried out using a computer program built with LabView. The electrode diameter was used as a calibration reference. During video capturing, the camera was placed at an angle of about 10° downward and an angle of about 10° backward. In the analysis, the effect of these angles was not taken into account. However, based on the geometry employed, it is estimated that average errors are of the order of 1.5%.

![Figure 5.3 Definition of reference points to monitor weld pool motion.](image)

Variation of the arc length during welding was monitored from the high-speed video pictures. In most cases the arc length was defined as the vertical distance between the lowest part of the pendant droplet and the point marked by the intersection of the wire axis and the weld pool surface as illustrated in figure 5.4. When the arc was turned aside (not perpendicular to the workpiece), the measurement of the arc length was carried out following the direction of the arc. The variation of the pendant droplet length was monitored by measuring the
distance between the upper liquid boundary at the wire tip and the bottom of the droplet (see figure 5.4).

Figure 5.4 High-speed video pictures a) before and b) after image processing and c) definition of arc length, droplet length and bright arc length.

To investigate the arc behaviour and its influence on the arc voltage in more detail, image processing was applied on the high-speed video pictures. The processing was carried out by converting the arc light intensity into a range of arbitrary greyscales. These greyscales can give a qualitative representation of the arc structure. This conversion was performed by the Phantom software. Examples of the high-speed video pictures before and after image processing are shown in figure 5.4. The length of the brightest arc region (as defined in figure 5.4c) was measured and related to the corresponding data of arc voltage and arc length.
5.2.4 Electrical signal monitoring system and data analysis

The measurement of the electrical signals was carried out using similar equipment as described in chapter 3. The sampling rate was 2000 Hz and the measuring time was 15.8 s. To determine the frequency of liquid metal oscillation, FFT analysis was applied on the voltage signals in between two pulses starting 5 ms after the first pulse. The reason for this time delay is to allow the free falling droplet to transfer through the arc to the weld pool. Before performing the analysis, the voltage signals were pre-processed following a procedure described by Barborak and Richardson.\[9\] The DC component was removed from the voltage signals and then the signals were filtered using a Butterworth band-pass filter with a filter order of 6. The cut-off frequencies of the band-pass filter were 10-500 Hz. Subsequently, the signals were windowed using a Hanning window. Typical voltage signals before and after band-pass filtering are presented in figures 5.5a and b respectively. The signals after being Hanning windowed can be seen in figure 5.5c.

The pulse frequency used in the experiments with P-GMA welding is much higher than that used in the experiments with GTA welding (Chapter 3). This higher pulse frequency leads to a limited amount of data points in between two pulses. For a pulse frequency of 32 Hz for instance, a time period of 28 ms between pulses is available for analysis. With a sampling rate of 2000 Hz per channel, this period is equivalent to 56 data points. Of the 56 data points, 32 points can be used for analysis to satisfy the requirement that the number of data points for FFT analysis is $2^n$. Since the resolution of an FFT analysis is equal to the data acquisition rate divided by the number of the data points, a frequency resolution of 62.5 Hz is obtained for this example. For higher pulse frequencies, the frequency resolution will be even lower as the time between the pulses is reduced. To improve the representation of the frequency resolution, zero-padding was applied.\[10\] This was performed by appending zero values to the end of a signal data after being windowed (figure 5.5d). Typically 256 data points for FFT analysis were obtained after zero-padding, which yielded a resolution frequency of 7.8 Hz. The results of the FFT analysis of voltage data without and with zero padding can be seen in figure 5.6.
Figure 5.5  a) Original voltage data, b) after applying band-pass filter, c) after applying band-pass filter and Hanning window and d) after applying band-pass filter, Hanning window and zero padding.

Figure 5.6  FFT results of voltage signals a) without zero padding and b) with zero padding.
5.3 Results

5.3.1 High-speed video observation

To study the behaviour of the liquid metal and the arc during P-GMA welding, experiments were carried out using various parameters given in table 5.2. The results of high-speed video observations made during these experiments are presented in this section.

The pendant droplet

High-speed video pictures show that in most cases, the pendant droplet under welding conditions used in the experiments oscillates up and down during the base current period. Typical pendant droplet oscillations can be seen in figure 5.7, which shows the dynamics of a pendant droplet in between two successive current pulses with a pulse frequency of 32 Hz. In this figure the droplet is detached just before the current switches back to the base level \( t = 3.5 \text{ ms} \). After that, the remaining liquid metal at the electrode tip moves up to its highest position \( t = 5.0 \text{ ms} \) and then moves down again until \( t = 6.5 \text{ ms} \). This up-and-down motion takes place a few times during the entire base current period. The moments at which the pendant droplet reaches its highest position are indicated by triangles. As the base period progresses, the pendant droplet grows slightly and the oscillation period increases from 2.5 ms at the beginning of the base current period to 3.5 ms at the end. The pendant droplet oscillation can be observed until \( t = 23.0 \text{ ms} \) after which it becomes less apparent.

In figure 5.8 frequencies of pendant droplet oscillation are plotted as a function of equivalent droplet diameter \( D_{eq} \). The equivalent droplet diameter represents the diameter of a sphere, the volume of which is equal to the volume of the pendant droplet. The oscillation frequency was obtained from the reciprocal of the oscillation period. Oscillation frequencies of 400 Hz to 100 Hz are observed for droplet equivalent diameters of 1.1 mm to 1.8 mm. Figure 5.8 shows that the frequency of the pendant droplet oscillation decreases with increasing equivalent droplet diameter. It should be noted that the video capturing was carried out at a framing rate of 2000 frames per second (interval period of 0.5 ms). With this framing rate, the determination of the droplet oscillation period may contain an error of \( \pm 0.25 \text{ ms} \) (one half of the interval period). As a result, the oscillation frequency may contain a relative error, which varies from 2 % for an oscillation frequency of 100 Hz to 11 % for an oscillation frequency of 400 Hz.
Figure 5.7 Pendant droplet oscillation during P-GMA welding with $f_p = 32$ Hz, and $v = 5$ mm s$^{-1}$. The numbers below the pictures indicate time in ms.
The free falling droplet

After being detached from the electrode tip, the droplet transfers to the weld pool. High-speed video pictures show that the transferring droplet also oscillates on its way towards the weld pool. In figure 5.9 the behaviour of a free falling droplet during P-GMA welding with a pulse frequency of 32 Hz is presented. The oscillation manifests itself by the variation of the length of the droplet’s main axes. The period of the oscillation in this example appears to be 3 ms ($t = 35.5$ ms to $38.5$ ms).

Figure 5.9 Oscillation of a falling droplet during P-GMA welding with $f_p = 32$ Hz and $v = 5$ mm s$^{-1}$. The numbers below the pictures indicate time in ms.
More apparent falling droplet oscillation can be observed when the droplet diameter is noticeably smaller than the arc length. This, for instance, can be seen in the first few seconds after starting the welding process, i.e. after arc ignition, during which the process is approaching its stable condition. In this situation a very long arc is obtained and several cycles of transferred droplet oscillation are displayed. It was stated in section 5.2 that with a pulse current of 290 A one droplet is detached per pulse. With a pulse frequency of 53 Hz, occasionally, a secondary droplet is produced during droplet detachment. In such a case a number of oscillation cycles can also be observed during the free flight period.

In figure 5.10, the oscillation frequencies of free falling droplets measured during experiments with pulse frequencies of 32 Hz and 53 Hz are plotted as a function of the equivalent droplet diameter. Droplets that oscillate a few times before plunging into the weld pool were selected for this analysis. As in the case of pendant droplet oscillation, the free droplet oscillation frequency was obtained from the reciprocal of the oscillation period. With this approach a relative error, which varies from 9 % for an oscillation frequency of 300 Hz to 33 % for an oscillation frequency of 1000 Hz is expected. As can be seen in the figure, the free droplet oscillation frequency decreases with increasing equivalent droplet diameter.

![Figure 5.10 Free droplet oscillation frequency as a function of equivalent droplet diameter.](image)
The weld pool

High-speed video pictures show that due to the impact of the droplets the weld pool is agitated and a travelling wave is generated. This phenomenon is observed in all welding conditions used in this study. More information of the weld pool dynamics however, can be obtained in the case of a 32 Hz pulse frequency compared with 53 Hz, due to a longer time between subsequent pulses. The dynamics of the weld pool during welding with a pulse frequency of 32 Hz are presented in figures 5.11 and 5.12 for partial and full penetration conditions respectively. The partially penetrated weld pool was produced on a 6 mm thick steel plate and the fully penetrated weld pool on a 2 mm thick steel plate.

The liquid waves in P-GMA welding are triggered primarily by the impact of the droplet, not by the change in the arc pressure during the current pulse. This can be seen in figure 5.11 where the surface of the weld pool after the current pulse ($t = 4$ ms) is similar to that before the pulse ($t = 0.5$ ms).

The back and forth motion of the liquid metal in the weld pool can be seen from the change in the position of the wave crests (indicated by white arrows) in figures 5.11 and 5.12. This motion is more clearly indicated in the schematic illustration shown in figure 5.13. Due to the impact of the droplet, the weld pool is depressed creating a trough surrounded by a circular crest (figure 5.13b; see also at $t = 7.0$ ms in figures 5.11 and 5.12). The crest starts moving in a radial outward direction. The part of the wave that moves backward continues its path to the rear part of the weld pool and is regarded as the primary wave (figure 5.13c). The part of the wave that moves forward is reflected by the leading edge of the weld pool. The combination of this reflection and the action of the surface tension fills the trough and forms a secondary wave. This secondary wave moves to the rear part of the weld pool following the primary wave. The backward motion of both waves is illustrated in figure 5.13d (see also the white arrows at $t = 9.5$ ms and 11.0 ms in figure 5.11 and at $t = 9.0$ ms and 13.5 ms in figure 5.12). Upon reaching the trailing edge, the primary wave is reflected forward (figure 5.13e). The secondary wave, which continues its backward motion will interfere with the reflected primary wave (figure 5.13f) and is reflected by the weld pool trailing edge (figure 5.13g). After this sequence both waves will move to the front of the weld pool (figure 5.13h).
Figure 5.11 Weld pool oscillation during P-GMA welding with $f_p = 32$ Hz and $v = 5 \text{ mm s}^{-1}$ in the case of partial penetration.
Figure 5.12 Weld pool oscillation during P-GMA welding with $f_p = 32$ Hz and $v = 5 \text{ mm s}^{-1}$ in the case of full penetration.
In the case of 53 Hz pulse frequency a complete back and forth wave motion cannot be observed because when the wave reaches the weld pool trailing edge, the subsequent pulse is applied and another droplet is transferred triggering another liquid wave.

Analysis of the weld pool dynamics was carried out by measuring the height of the weld pool surface on the high-speed video pictures at defined positions, as described in section 5.2. The results of analysis for partially and fully penetrated weld pools produced with a pulse frequency of 32 Hz are presented in figures 5.14a and b respectively. The blank regions between $t = 0$ ms to 3.5 ms in the figures correspond with the current pulse during which the intensity of the arc light is so high that the weld pool surface cannot be observed. In both figures, a sharp increase in the pool height underneath the electrode (about 2 mm from the pool leading edge) at $t = 5$ ms corresponds with the impact of the detached droplet on the weld pool. During this event the total weld pool height is taken as the sum of the weld pool height and the droplet length. It should be noted that the visibility of the weld pool is limited with respect to the indentation inside the circular crest just after the droplet impact; despite this, acceptable observation of the weld pool dynamics can be carried out.

In the partial penetration case (figure 5.14a), the back and forth motion of the liquid wave can be identified by the occurrence of peak $P1$ at the front of the weld pool ($t = 9.5$ ms), peak $P2$ at the rear of the weld pool ($t = 20.5$ ms) and peak $P3$ at the front of the weld pool ($t = 31.5$ ms), before the subsequent
current pulse is applied. In the full penetration case (figure 5.14b), this motion can be identified by the occurrence of peaks $P1$, $P2$ and $P3$ at $t = 7.5$ ms, 22.0 ms and 31.5 ms respectively. However, no complete back and forth motion was observed between pulses (in figure 5.14b peak $P3$ is not situated on the same reference with peak $P1$).

Figure 5.14 Image analysis of the oscillatory behaviour of a) partially and b) fully penetrated weld pool during P-GMA welding with $f_p = 32$ Hz and $v = 5$ mm s$^{-1}$.
The analyses of weld pool dynamics, as presented in figure 5.14, were carried out for welds made at a travel speed of 5 mm s\(^{-1}\). To study the dynamics of different pool sizes in both partial and full penetration cases, experiments with a pulse frequency of 32 Hz were carried out by changing the travel speed to 3 and 7 mm s\(^{-1}\). Weld pool lengths and wave speeds were revealed from the high speed video pictures. The measurement of the wave speed was carried out by following the crest during movement to the rear of the weld pool. The results of the measurement are presented in table 5.3. Note that the wave speed of the fully penetrated weld pool when the welding speed is 3 mm s\(^{-1}\) cannot be revealed due to very complex liquid motions.

Figure 5.15 Partially (left) and fully (right) penetrated weld pools during P-GMA welding with \(f_p = 32\) Hz and various travel speeds.
As expected, with a lower travel speed a larger weld pool is produced (see figure 5.15). In addition, the wave speed was found to be almost constant. A change in the wave behaviour between partially and fully penetrated weld pools was not observed.

<table>
<thead>
<tr>
<th>Weld pool penetration</th>
<th>Travel speed</th>
<th>Weld length</th>
<th>Wave speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial penetration</td>
<td>3 mm s⁻¹</td>
<td>10.7 mm</td>
<td>0.76 m s⁻¹</td>
</tr>
<tr>
<td></td>
<td>5 mm s⁻¹</td>
<td>9.3 mm</td>
<td>0.77 m s⁻¹</td>
</tr>
<tr>
<td></td>
<td>7 mm s⁻¹</td>
<td>8.6 mm</td>
<td>0.81 m s⁻¹</td>
</tr>
<tr>
<td>Full penetration</td>
<td>3 mm s⁻¹</td>
<td>not available</td>
<td>not available</td>
</tr>
<tr>
<td></td>
<td>5 mm s⁻¹</td>
<td>14.9 mm</td>
<td>0.71 m s⁻¹</td>
</tr>
<tr>
<td></td>
<td>7 mm s⁻¹</td>
<td>14.1 mm</td>
<td>0.72 m s⁻¹</td>
</tr>
</tbody>
</table>

The arc

High-speed video observations show that during P-GMA welding, the arc length and the arc structure vary. The variation of the arc length and the arc structure were analysed using the procedure described in section 5.2.3. The arc length was quantified by measuring the distance between the bottom of the droplet and the weld pool. The change in arc structure was revealed by converting the arc light intensity into different greyscales. High-speed video pictures, after image processing, are presented in figure 5.16. These pictures show the variation of the arc structure during welding with $f_p = 32$ Hz in the partial penetration case. The changes in arc structure were quantified by measuring the length of the highly illuminated zone, i.e. the bright arc length.

The measured arc length and the bright arc length for welding with a pulse frequency of 32 Hz for partial and full penetration conditions are plotted as a function of time in figure 5.17. The measured droplet length and the height of the weld pool are also plotted. Figure 5.17 shows that the arc length oscillates out of phase with respect to the droplet oscillation. The influence of the weld pool dynamics on the arc length appears to be limited. Figure 5.17 also shows that the frequency of the bright arc length oscillations is in good agreement with the frequency of droplet oscillations. However, a small time delay of about 0.5 ms to 1 ms between the bright arc length and the droplet oscillations can be observed.
Figure 5.16 The change in arc structure during partial penetration P-GMA welding with $f_p = 32$ Hz and $v = 5$ mm s$^{-1}$.
### Summary of visual observation

It has been indicated in this section that for various welding conditions, the remaining molten liquid at the wire tip oscillates after the current pulse. It is also shown that the droplet oscillation frequency decreases with increasing droplet size (see figure 5.8). For a constant peak time, a droplet is detached by a single pulse or by multiple pulses dependent on the magnitude of the peak current. It is shown in figure 5.9 that the detached droplet oscillates on its way...
to the weld pool. Similar to the case of pendant droplet oscillation, a decreasing oscillation frequency with increasing droplet size is demonstrated.

Generation of liquid waves in the weld pool during P-GMA welding was observed due primarily to the impact of the droplet. This travelling (back and forth) wave was detected in the case of both partial and full penetration. Characterisation of the liquid wave is restricted by the base current time, and only one complete back and forth motion can be observed in between the pulses. Direct measurement from the high speed video yields an almost constant wave propagation speed of approximately 0.75 m s\(^{-1}\) for both partial and full penetration conditions.

It was observed from the high-speed video images that the dynamics of the liquid droplet during P-GMA welding directly influence the arc length. In contrast the influence of the weld pool dynamics on the arc length appears to be limited. It was also observed that as the droplet oscillates and grows the arc structure changes. The change of the arc structure was revealed by dividing the arc into two regions based on the arc light intensity. The frequency of bright arc length oscillation is in good agreement with the frequency of droplet oscillation, but a small time delay of about 0.5 to 1 ms between the maxima of the bright arc length and the droplet oscillation can be observed.

### 5.3.2 Voltage monitoring

To explore the possibility to monitor the weld pool and droplet dynamics during P-GMA welding from the electrical signals, the voltage and the current were measured during the experiments. Typical voltage and current signals for a pulse frequency of 32 Hz are presented in figure 5.18. It is seen in the figure that the voltage increases to about 33 V when the peak current is applied. When the current is switched back to its base level, the voltage decreases to around 20 V. During the base current period, the voltage oscillates with an amplitude of approximately 0.5 V and a period in the range of 2.0 ms to 4.5 ms.

An FFT analysis of the voltage variation was performed to reveal information about the liquid metal dynamics. The analysis was carried out for a set of voltage data points in between two pulses. To omit any influence of the free falling droplet on the results of the analysis, the data from the first 5 ms after the pulse are excluded. The procedure for this analysis was described in section 5.2.4. In comparison to \(f_p = 53\) Hz, a longer period of time between
pulses, and thus more information about phenomena taking place, can be obtained in the case of $f_p = 32$ Hz. For this reason, the results of voltage monitoring and FFT analysis in this section are only presented for the case of a 32 Hz pulse frequency.

![Figure 5.18 Voltage and current signals during partial penetration P-GMA welding with $f_p = 32$ Hz and $v = 5$ mm s$^{-1}$.](image)

Voltage signals and the corresponding FFT results for welding under partial and full penetration conditions with a pulse frequency of 32 Hz and a travel speed of 5 mm s$^{-1}$ are presented in figures 5.19 and 5.20 respectively. In figures 5.19a and 5.20a the voltage after three successive welding current pulses as a function of time are shown. Each successive signal has been offset by 1 V for clarity. The figures show that the voltage in between two pulses has a similar oscillation pattern. The amplitude of this oscillation is approximately 0.5 V and the period is approximately 3.5 ms. Figures 5.19a and 5.20a also show that the overall voltage signal during the base current period has a concave shape (decreasing until about 15 ms and then increasing again). This concave shape is indicated by the dashed line in figure 5.21. The results of FFT analysis are presented in figures 5.19b and 5.20b. The figures show two dominant frequencies of about 50 Hz and in about 300 Hz for both welding conditions, which are related with the concave voltage trend and the oscillation frequency of the pendant droplet respectively.
Figure 5.19 a) Voltage signals after three successive pulses and b) FFT results for partial penetration P-GMA welding with $f_p = 32$ Hz and $v = 5$ mm s$^{-1}$. Each successive voltage signal has an offset of 1 V.

Figure 5.20 a) Voltage signals after three successive pulses and b) FFT results for full penetration P-GMA welding with $f_p = 32$ Hz and $v = 5$ mm s$^{-1}$. Each successive voltage signal has an offset of 1 V.

Voltage signals for welding travel speeds of 3 and 7 mm s$^{-1}$ show similar oscillation patterns to those presented in figures 5.19a and 5.20a. The corresponding FFT results also show two dominant frequencies of about 50 Hz and 300 Hz. These dominant frequencies are summarised in table 5.4.
Figure 5.21 Typical trend (shown by a dashed line) of the measured voltage during the base period as a function of time ($f_p = 32$ Hz and $v = 5$ mm s$^{-1}$).

<table>
<thead>
<tr>
<th>Weld pool penetration</th>
<th>Travel speed</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial penetration</td>
<td>3 mm s$^{-1}$</td>
<td>39 and 335 Hz</td>
</tr>
<tr>
<td></td>
<td>5 mm s$^{-1}$</td>
<td>47 and 304 Hz</td>
</tr>
<tr>
<td></td>
<td>7 mm s$^{-1}$</td>
<td>47 and 320 Hz</td>
</tr>
<tr>
<td>Full penetration</td>
<td>3 mm s$^{-1}$</td>
<td>55 and 320 Hz</td>
</tr>
<tr>
<td></td>
<td>5 mm s$^{-1}$</td>
<td>55 and 304 Hz</td>
</tr>
<tr>
<td></td>
<td>7 mm s$^{-1}$</td>
<td>not available</td>
</tr>
</tbody>
</table>

Summary of voltage signal monitoring and analysis

The results of electrical signal measurement during P-GMA welding show variation of voltage signals. The increase of the arc voltage with a magnitude of approximately 13 V when the current is switched from the base to the peak level is not surprising as it is a direct consequence of the change in the operating point.
The variation of the voltage during the base current period contains interesting features. This variation was observed during welding under various conditions. FFT analysis of the voltage reveals two frequency regions, one at about 50 Hz, which is related with the concave voltage trend and the other at about 300 Hz, which appears to be corresponded to the oscillation frequency of the pendant droplet. It can be expected that the variation of the voltage measured during the experiment is caused by the change in the arc length. The occurrence of the concave voltage trend, however, is unexpected since in this situation the wire is fed continuously and the arc length will decrease accordingly. The non proportional relationship between the voltage and the arc length was also indicated by increasing voltage when the arc length reduces during droplet oscillation. To further clarify this physical phenomenon the voltage signals are correlated with the arc structure and discussed in the following section.

5.4. Discussion

The wire - arc - weld pool system shows a highly dynamic behaviour during P-GMA welding. As presented in the previous section each of these zones will influence the measured voltage signals. In this section, attempts are made to explain the observed phenomena and to disentangle the contributions of the different zones of the system on the voltage.

In this discussion first the two liquid bodies, i.e. the droplet and the weld pool will be considered. Secondly, the behaviour of the electric arc will be discussed and finally, the influence of the liquid metal and the arc structure on the arc voltage will be described.

5.4.1 Pendant droplet behaviour

It is believed that the pendant droplet oscillation observed during the experiments is caused by the combination of the electromagnetic Lorentz force, the surface tension and the action of gravity. During the current pulse, the pendant droplet is pinched off by the Lorentz force generated in the droplet. When a droplet is detached some molten metal will stay at the electrode tip forming a pendant droplet. If only a small amount of liquid is left, oscillation was not observed. If the leftover liquid metal at the electrode tip is stretched after droplet detachment (observed when there is enough liquid metal left at the
electrode tip), it will be brought to the equilibrium position by the surface tension. When the current is switched to the base level, the electromagnetic force acting on the droplet is suddenly lowered and the leftover droplet starts oscillating by the combined action of surface tension and gravity. During the base time the oscillation signal will damp.

In the case that the droplet is not detached by the current pulse (as in the case of welding with a peak current of 230 A), the pendant droplet is triggered into oscillation by a similar mechanism; *i.e.* stretched by the electromagnetic force during the peak current and brought into oscillation by the combined action of surface tension and gravity.

In fig 5.8 it was shown that the oscillation frequency of the pendant droplet, obtained from visual observation, depends on the droplet size. Smaller droplets oscillate at a higher frequency. This is in agreement with the observation of the pendant droplet during GTAW with cold-wire addition reported in chapter 3. Under the condition where one droplet is detached per current pulse, as in this work, the pendant droplets oscillate with a frequency in the range of 250-400 Hz. During this oscillation the pendant droplet changes its length periodically with a magnitude of up to almost 1 mm.

### 5.4.2 Weld pool behaviour

Visual observations show that the liquid waves are triggered by the impact of the droplet. The arc pressure, which initiates the oscillation in GTA welding, has a negligible effect. This could be partly caused by the formation of a long arc length and the detachment of the droplet. In the case of P-GMA welding with a pulse frequency of 32 Hz, for instance, the arc length just before the current pulse was found to be approximately 3.3 mm (see figures 5.11 and 5.12), whereas the maximum arc length in GTA welding as described in chapter 2 was in the order of 2.4 mm. While the longer arc in P-GMA welding is required to prevent short-circuiting of the electrode and the workpiece, this will reduce the arc pressure on the weld pool surface. Lin and Eagar\[^{[11]}\] reported that the arc pressure can be expressed as:

\[
P_{arc} = \frac{\mu_d I J}{4\pi},
\]

(5.1)
where $\mu_0$ is the magnetic permeability of free space, $I$ the welding current and $J$ the current density.\textsuperscript{[11]} As can be seen, the arc length is not included in equation (5.1). However, according to Xiao\textsuperscript{[12]} the arc length influences the current density. The shorter the arc length the higher the current density and, therefore, the higher the arc pressure on the weld pool. It is expected that the reduction of the current density with increasing arc length is due to the increased contact area between the arc and the weld pool.

If a droplet is detached during the peak current period, the role of the current pulse to trigger the liquid waves is also limited by the detaching droplet. Instead of depressing the weld pool the arc pressure depresses the surface of the free falling droplet.

It can be seen in figures 5.11 and 5.12 that a deep surface depression due to the current pulse, as observed on the GTA weld pool, is not visible on P-GMA weld pools. Besides being influenced by the longer arc length, this is also caused by the curved shape of the GMA weld pool. The arc force depresses the surface leading to the deformation of the weld pool shape as depicted in figure 5.22. This deformation can also be seen after the current pulse in figures 5.11; however the amplitude is small.

![Figure 5.22 Schematic illustration of weld pool surface deformation during GMA welding due to arc pressure.](image)

High speed video images revealed that the weld pool behaviour for partially and fully penetrated weld pools is similar. In both cases the motion on the surface of the weld pool can be regarded as travelling waves. Oscillation mode 1, reported in the past for S-GMA welding is not observed. As shown in figure 5.13, a trough surrounded by a circular crest is formed on the weld pool due to the impact of the droplet, which appears to be similar to oscillation mode 1. However, unlike the liquid motion in oscillation mode 1, after the trough is filled the liquid wave moves backward to the rear of the weld pool.
The oscillation sequence should not be confused with the situation in GTA welding, where oscillations of a standing wave is considered. This implies that the existing analytical model to characterise the oscillatory behaviour of the weld pool described in chapter 2 may not be applicable for a P-GMA welding, since the models are developed assuming a standing wave on a flat weld pool.

If the travelling liquid wave in the weld pool can be characterised as a capillary wave, then the surface tension dominates. The wavelength of the capillary wave is much shorter than the so called critical wavelength. Waves with a wavelength higher than the critical wavelength are dominated by gravity. The critical wavelength $\lambda_{crit}$ is given by the equation:

$$\lambda_{crit} = \frac{2\pi \sqrt{\gamma \rho}}{g},$$  \hspace{1cm} (5.2)

where $\gamma$ is the surface tension, $\rho$ the density and $g$ the acceleration due to gravity. Taking the surface tension and the density of liquid steel as given in table 5.5, and $g = 9.8 \text{ m s}^{-2}$ a critical wavelength of approximately 24 mm is obtained, which is longer than the weld pool length.

| Table 5.5  Material properties of liquid steel.\[12\] |
|-----------------|------------------|
| surface tension $\gamma$ | 1.0 N m$^{-1}$ |
| density $\rho$ | 7000 kg m$^{-3}$ |

Leng\[14\] suggested that the wavelength of a liquid wave generated by droplet impact is equal to the droplet diameter. The droplet diameter observed in the present study, particularly when a one droplet per pulse situation is obtained, is found to be 1.5 mm. The velocity of a capillary wave $v$ is given by:\[14\]

$$v = \sqrt{2\pi \gamma / \lambda \rho},$$  \hspace{1cm} (5.3)

where $\lambda$ is the wavelength. Taking the droplet diameter (1.5 mm) as the wavelength and material properties from table 5.5 a velocity of 0.77 m s$^{-1}$ is obtained from equation 5.3. This velocity is in the same order of magnitude as the velocity observed with the high-speed video (0.71-0.81 m s$^{-1}$). Therefore, it can be concluded that the observed travelling wave is surface tension controlled. It should be noted that the flow due to metal addition is also likely to influence the wave velocity. The extent of this influence however, is difficult to determine on the basis of the results obtained.
A change in the wave behaviour between partially and fully penetrated weld pools was not observed. This can be related to the extent of the solid close to the weld root supporting the pool, which was also described by Xiao\textsuperscript{12} in the case of GTA welding. Xiao reported that when the ratio between the top and the bottom diameter of a fully penetrated weld pool is less than 0.5, the weld pool will behave similar to the partially penetrated pool. In the present study, the weld pool is elongated. When the bottom width of the fully penetrated pool is relatively small, the supporting solid metal will prevent the liquid motion at the bottom of the weld pool. However, when the pool bottom width enlarges the weld pool sags suddenly. The liquid dynamics become very complex and difficult to characterise.

5.4.3 Arc behaviour

Observations of the high-speed videos show that the arc in P-GMA welding exhibits a more dynamic behaviour compared to the GTA welding arc. After the peak current period, the arc switches its attachment from the bottom of the droplet to the surface of the leftover droplet at the tip of the electrode. As the wire electrode is continuously fed, the arc length reduces. The root of the arc on the cathode can deviate to the front or to the centre of the weld pool due to the change in the location of oxides which are preferable spots for electron emission. The high-speed videos also show that as the base time progresses, the pendant droplet grows and the arc structure alters. The alteration of the arc structure is characterised by a change in the geometry of the bright arc region as presented in section 5.4.3. It can be seen in figure 5.16 that the size of the bright arc changes during pendant droplet oscillation and during pendant droplet growth.

One possible explanation for the change in the arc brightness is related to the metal vapour content. As the surface area of the droplet contacting the arc enlarges, more metal vapour is released. These observations are in line with the results of the work by Deam \textit{et al.}\textsuperscript{15}, where an increase of metal evaporation rate was reported with increasing droplet size. A number of studies\textsuperscript{16-18} have shown that the presence of metal vapour in the arc column will lead to a significant increase of the emission coefficient $\varepsilon$ of the plasma. The higher plasma emission coefficient due to a higher metal vapour content is presented in figure 5.23.
Working with plasma-GMA welding, Ton\textsuperscript{[19]} reported that a very bright region was observed in the inner core of the arc. Spectroscopic measurements showed that high amounts of metal vapour due to the evaporating electrode exist in the inner arc core. It can be deduced that the bright arc region, observed in the present study, consists of a higher level of metal vapour compared to the non-bright (normal) arc region.

![Image](image.png)

Figure 5.23 The influence of iron vapour on the emission coefficient of Ar/Fe plasma.\textsuperscript{[20]}

### 5.4.4 Influence of the weld pool, the droplet and the arc on the voltage

In this section the influence of the different regions in the welding system, \textit{i.e.} the wire electrode, the liquid droplet at the electrode tip, the electric arc, the weld pool and the workpiece, on the voltage is analysed. As described in chapter 2, the total voltage consists of the voltage across these regions. During welding, the physical condition of these regions changes even though the welding current is constant. As a result the total voltage during welding will also vary. In the following, visual observations of the different regions around the arc will be related to the measured voltage.

High-speed video observations show that the extension of the solid wire increases since it is fed continuously. It is also shown that the length of the pendant droplet changes periodically resulting in oscillation. In addition, as the base period progresses the pendant droplet becomes larger. It was also observed
that the weld pool is agitated by the impact of the transferred droplet. The change of the electrode extension and the pendant droplet oscillation in combination with the agitation of the weld pool will change the arc length. To relate the measurements of the different regions of the welding system to the measured voltage, some assumptions are made.

Firstly, the voltage changes in the weld pool and workpiece are considered to be negligible. Therefore, the total voltage $U$ during welding can be expressed as the sum of the voltage drop along the solid wire $U_w$, the voltage drop over the pendant droplet $U_d$ and the voltage drop across the arc $U_{\text{arc}}$ (see figure 5.24) \textit{i.e.}:

$$U = U_w + U_d + U_{\text{arc}}.$$ \hspace{1cm} (5.4)

Secondly, it is assumed that the solid wire has a cylindrical shape with a constant diameter of 1 mm and has a fixed contact with the contact tube at the end of the tube. It is also assumed that the droplet has a cylindrical shape with varying diameter and length due to oscillations, but the current flows through the droplet across a constant diameter of 1 mm.

Following Ohm’s law and taking $l_w$ and $l_d$ as the length of the solid wire and the pendant droplet respectively, $\rho_w$ and $\rho_d$ as the mean resistivity of the solid wire and the pendant droplet respectively, $I$ as the welding current and $A_w$ and $A_d$ as the current carrying areas of the wire and the pendant droplet cross-sections respectively, equation (5.4) can be expressed as:
\[ U = \frac{l_w \rho_w}{A_w} I + \frac{l_d \rho_d}{A_d} I + U_{\text{arc}}. \] (5.5)

In reality the resistivity is temperature and therefore position dependent. The temperature dependent resistivity of steel is presented in figure 5.25.\textsuperscript{[21]} In the analysis, however, the resistivity is considered to be constant. Based on figure 5.25, resistivity values of 1 mΩ mm and 1.4 mΩ mm are used for the solid wire and the liquid droplet respectively.

Using the foregoing assumptions and the measured values of wire extension and droplet length, the voltage drops over these two regions are calculated and subtracted from the total voltage. The resulting voltage patterns are thus related to the welding arc. Figure 5.26 shows typical calculated voltage variations across the wire, the droplet and the arc. For comparison, the measured total voltage is also plotted. It is seen in the figure that the voltage over the wire extension and the pendant droplet are constant relative to the voltage across the arc. Apparently, the variations of the total voltage are primarily caused by the voltage variations over the arc. Calculations for other welding conditions give similar results.
Liquid metal and arc behaviour during pulsed-current GMA welding

It is commonly accepted that the arc voltage is proportional to the arc length. As described in chapter 2, the arc voltage $U_{\text{arc}}$ can be divided into three parts, the voltage drops over the anode fall region $U_{\text{an}}$, over the arc column $U_{\text{col}}$ and over the cathode fall region $U_{\text{cat}}$, so that:

$$U_{\text{arc}} = U_{\text{an}} + U_{\text{cat}} + U_{\text{col}}. \quad (5.6)$$

$U_{\text{an}}$ and $U_{\text{cat}}$ can be considered to be constant whilst $U_{\text{col}}$ is related to the arc length $l_{\text{arc}}$ following:

$$U_{\text{col}} = EL_{\text{arc}}, \quad (5.7)$$

where $E$ represents the (average) electric field strength. It can therefore be expected that the voltage variations observed in this study are caused by the change in the arc length. However, there is no proportional relationship between the arc voltage and arc length. In figure 5.27 the arc voltage and the arc length in between two pulses are plotted as a function of time. The figure shows that during this base current period, the arc length decreases (see the dashed line) as the wire is fed continuously. However, the voltage decreases until $t = 20$ ms,
and then unexpectedly increases again to $t = 32$ ms (see the concave dotted line). After $t = 32$ ms another current pulse is applied. If $E$ is constant, the voltage trend should decrease continuously with the arc length. Figure 5.27 also shows that when the voltage oscillates a number of times between $t = 7.5$ ms and $t = 32$ ms, the voltage maxima occur coincidently with the minima instead of with the maxima of the arc length.

A non-proportional relationship between the arc voltage and the arc length has been reported earlier by other researchers. Ponomarev et al.\cite{21} observed that the arc voltage increased progressively when the droplet grew during which the arc length was decreasing (figure 5.28). This was explained by the assumption that the resistance of the droplet is higher than that of the solid filler wire. Consequently, as the droplet grows the voltage across the liquid metal increases and counteracts the voltage drop due to the decrease of arc length. However, it can be argued that the influence of the voltage variation due to droplet growth on the total voltage variation is too small to justify this explanation, as shown in figure 5.26.

Figure 5.27 Arc voltage $U_{arc}$ (---) and arc length (−−−) for welding with $f_p = 32$ Hz and $v = 5$ mm s$^{-1}$ in partial penetration.
Zhu and Simpson\textsuperscript{[22]} reported that during GMA welding of steel, the voltage increased when the droplet grew and then decreased sharply as the droplet detached. The authors propose that this voltage fluctuation is caused by the change in the resistance caused by the necking of the liquid droplet just before detachment, and the geometrical change of the arc due to the transferred droplet. This description, however, cannot explain the voltage fluctuation during the base current period, where the droplet necking is not significant and the transferred droplet is completely immersed in the weld pool.

An abnormal voltage increase during welding of aluminium with argon shielding gas has been observed by Tong \textit{et al.}\textsuperscript{[23]} They reported that during P-GMA welding, short-circuiting might occur after the current pulse. When the arc is reignited immediately after the liquid bridge breaks, a bright constricted arc is formed between the wire electrode and the weld pool. At the same time the arc voltage surges to a level of that during the peak current. It is explained that this unusual voltage upsurge is caused by the lack of oxides on the cathode increasing the work function (the cathode fall voltage increases to ease the emission of electrons). In addition, due to the narrowing of the arc root on the cathode, the current density increases, and thus the potential gradient across the contraction space (the transition area between the cathode fall and the plasma column). This phenomenon, however, is only observed at the beginning of the
base current period (up to 3 ms after the current pulse). After that, the concentrated cathode spot disperses to the weld pool edge and the potential gradient across the cathode fall space is reduced. Unlike the phenomenon observed by Tong et al., the unexpected voltage behaviour observed in the present study takes place during the entire base current period. It is unlikely that this voltage behaviour is caused by the contraction of the arc root on the cathode, as no evidence for such a contraction was found from observations.

A more likely explanation of the unusual voltage fluctuation observed in the present study is based on the presence of metal vapour in the arc. It is known that the presence of metal vapour leads to an increase of the electrical conductivity (see figure 5.29) and the emission coefficient of the plasma (see figure 5.23). These phenomena have different effects on the voltage. In response to the experimental findings presented in this work Lowke et al. explained that on the one hand, the increase of electrical conductivity due to the metal vapour tends to reduce the voltage; on the other hand the increase of the radiation emission tends to cool the arc, reducing the electrical conductivity and increasing the voltage. The markedly increased radiation of the arc can override the effect of increasing conductivity. As an implication, more energy is required to compensate the energy loss so that the voltage increases. Tashiro et al. found that the electrical conductivity of a He/Fe plasma increases with iron vapour content for a low iron vapour concentration (up to 5%). In the case of a higher iron vapour concentration (> 5%), the electrical conductivity is saturated and the effect of radiation loss due to the increasing emission coefficient becomes dominant. This radiation loss will result in a decrease of the plasma temperature. Due to a so called thermal pinch effect, the current path will be restricted in the vicinity of the arc axis, which in turn will lead to an increase of the current density, and thus the electric field strength and the voltage. The increase of the voltage due to metal vapour has been calculated by Lowke et al. According to their calculation in the case of a welding current of 200 A, the arc voltage for a pure argon arc was 11.4 V. In the presence of 30% iron vapour, the arc voltage was found to be 9.4 V, when only the influence on the electrical conductivity is taken into account. When both the electrical conductivity and the radiation emission are taken into account, they found an arc voltage of 27.8 V. The results of the calculation confirm that the arc voltage can increase with a higher concentration of metal vapour.
To account for the influence of the arc behaviour on the relationship between the arc length and the voltage, a simplified arc voltage model is proposed. In this model the arc column is divided into two regions, the bright arc and the normal arc regions (see figure 5.30), so that:

\[ U_{\text{col}} = U_{\text{ba}} + U_{\text{na}}. \]  (5.8)

Assuming that each arc region has a different electric field strength, \( E_{\text{ba}} \) for the bright arc and \( E_{\text{na}} \) for the normal arc; and taking \( l_{\text{ba}} \) and \( l_{\text{na}} \) as the
length of the bright arc and the normal arc respectively, the voltage over the arc can be expressed as:

\[ U_{\text{arc}} = U_{an} + U_{cat} + E_{ba}l_{ba} + E_{na}l_{na}, \]  

(H5.9)

Having \( U_{\text{arc}}, l_{ba} \) and \( l_{na} \) from experiments, \( U_{an} + U_{cat}, E_{ba} \) and \( E_{na} \) can be estimated using the multiple regression approach. Taking matrices \( y, \beta \) and \( X \) as:

\[
\begin{bmatrix}
U_{\text{arc}1} \\
U_{\text{arc}2} \\
\vdots \\
U_{\text{arc}n}
\end{bmatrix}, \quad \beta = \begin{bmatrix}
U_{an} + U_{cat} \\
E_{ba} \\
E_{na}
\end{bmatrix} \quad \text{and} \quad X = \begin{bmatrix}
1 & l_{ba1} & l_{na1} \\
1 & l_{ba2} & l_{na2} \\
\vdots & \vdots & \vdots \\
1 & l_{ban} & l_{nan}
\end{bmatrix},
\]

where:

\[ y = \beta X, \]  

(H5.10)

the value of \( \beta \) can be estimated by:[25]

\[ \beta = (X'X)^{-1}X'y, \]  

(H5.11)

where \( X' \) is the transpose of matrix \( X \) and \( (X'X)^{-1} \) the inverse of the product \( X'X \). In the case of welding with a pulse frequency of 32 Hz and a travel speed of 5 mm s\(^{-1}\), the multiple regression analysis (over the combined data of the partial and the full penetration condition) gives a value of 14.89 V for \( U_{an} + U_{cat} \), which is in reasonable agreement with the value reported in the literature (15.1 V).[26] The average field strength of the bright arc \( E_{ba} \) is found to be 1.66 V mm\(^{-1}\), higher than that of the normal arc \( E_{na} \) which is 1.13 V mm\(^{-1}\). To test the validity of these results, the \( U_{\text{arc}} \) obtained from the experiment (compensated for the voltage drops over wire and weld pool) is plotted as a function of the \( U_{\text{arc}} \) from the calculations using equation (5.9). The plot is presented in figure 5.31. The straight line in the figure represents the condition where the experimentally obtained \( U_{\text{arc}} \) is equal to the calculated \( U_{\text{arc}} \). The figure shows reasonable agreement between both values although some deviations occur. These
deviations can be caused by variations of the arc geometry, for instance due to contraction or expansion of the arc, and changes in the location of the arc root on the workpiece; which in turn can influence the effective arc length, and thus the voltage data.

Figure 5.31 Comparison between $U_{arc}$ obtained from experiments and $U_{arc}$ from calculations.

In figure 5.32, $U_{arc}$, $U_{ba}$ and $U_{na}$ are plotted as a function of time for partial penetration welding with $f_p = 32$ Hz and $I_p = 290$ A. $U_{ba}$ and $U_{na}$ were calculated using $E_{ba} = 1.66$ V mm$^{-1}$ and $E_{na} = 1.13$ V mm$^{-1}$. For comparison, the total arc length, the bright arc length and the normal arc length are plotted in figure 5.33. Figure 5.32 shows that as time progresses $U_{na}$ decreases but $U_{ba}$ increases. Comparing figures 5.32 and 5.33, it can be seen that $U_{na}$ and $U_{ba}$ are proportional to the normal arc length and the bright arc length respectively. As a result the general trend of the arc voltage decreases to $t = 20$ ms and then increases again. This supports the observation that the total voltage can increase when the bright arc region is extended even though the total arc length reduces.

The results discussed above show that modelling the arc by separating the arc column into two arc regions yields a better relationship between the arc length and the voltage than the commonly used method; i.e. considering only one value for the average electric field strength $E$. 
Figure 5.31 Voltage across the arc $U_{\text{arc}}$ ($\rightarrow$), the bright arc $U_{\text{ba}}$ ($\leftarrow$) and the normal arc $U_{\text{na}}$ ($\rightarrow$) for welding with $f_p = 32$ Hz and $v = 5$ mm s$^{-1}$ in partial penetration.

Figure 5.32 The arc length ($\rightarrow$), the bright arc length ($\leftarrow$) and the normal arc length ($\rightarrow$) for welding with $f_p = 32$ Hz and $v = 5$ mm s$^{-1}$ in partial penetration.
5.5. Conclusions

On the basis of the results obtained, the following conclusions can be drawn.

During P-GMA welding the pendant and the detached droplets can be triggered into oscillation by the unbalanced surface tension created when the liquid metal at the wire tip is stretched by the electromagnetic Lorentz force during the current pulse. The oscillation of the pendant droplet can be easily monitored visually by high-speed video imaging. Visual monitoring of the detached droplet oscillation is constrained by the distance between the electrode and the weld pool. The experimental results show that the oscillation frequency of the pendant and the detached droplet decreases with increasing droplet size.

The weld pool is agitated and liquid waves are generated by the impact of the droplet, rather than by the arc pressure. Oscillation mode 1, reported in the past for S-GMA welding, is not observed. The liquid wave in a P-GMA weld pool behaves as a travelling wave in a back-and-forth mode for both partial and full penetration cases. The liquid wave can be characterised as a capillary wave and the wave velocity is found to be 0.7 to 0.8 m s\(^{-1}\). Information about weld pool dynamics cannot be extracted from the electrical signals during P-GMA welding under the conditions used in this work because the change in the effective arc length due to the pool dynamics is too small. In addition, the arc root on the workpiece is located at places where electrons are easily emitted, for instance at the oxides, which can be located at the weld pool edge and is not measurably influenced by weld pool dynamics. Another factor that makes monitoring weld pool oscillation using voltage measurements difficult is the non linear relationship between the arc length and the voltage.

In this work, two regions within the arc column can be distinguished based on the arc intensity, i.e. a bright arc region and a normal arc region. The modification of the arc structure takes place during the growth and the oscillation of the pendant droplet. As a larger droplet surface is exposed to the arc, the bright arc region adjacent to the pendant droplet is extended due to an increased metal evaporation rate. The modification of the arc structure leads to a non linear relationship between the arc length and the voltage. The presence of metal vapour leads to an increase of the electrical conductivity and the emission coefficient of the plasma. These phenomena have different effects on the voltage. Increasing electrical conductivity will reduce the voltage, but increasing radiation emission will increase the voltage. Apparently, the
increase of the emission coefficient in the bright arc region overrides the increase of the conductivity. This implies that when the total arc length decreases, the voltage can increase if the bright arc region enlarges. A conceptual model, proposed to explore this relationship, indicates that the average electric field strength of the bright arc region close to the electrode is 1.66 V mm\(^{-1}\), which is higher than that of the normal arc (1.13 V mm\(^{-1}\)).
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Chapter 6
General discussion and conclusions

6.1 General discussion

An experimental study has been carried out to study the oscillatory behaviour of the liquid metal (i.e. the weld pool and the pendant droplet) and the arc behaviour during cold-wire GTA welding and pulsed-current GMA (P-GMA) welding. In these processes a filler wire is introduced into the weld pool without being part of the electrical circuit and as part of the electrical circuit respectively. In the case of cold-wire GTA welding, current pulses were superimposed on the welding current to trigger weld pool oscillations. In P-GMA welding, current pulses were intended to detach metal droplets and to trigger weld pool oscillations. A set of high-speed video pictures showing the different welding processes used in this study are shown in figure 6.1.

The study on cold-wire GTA welding focused on uninterrupted and interrupted bridging transfer. Uninterrupted metal transfer takes place when a contact between the filler wire and the weld pool is maintained at the pool leading edge. As a result the liquid metal flows smoothly into the pool. Interrupted metal transfer takes place when the wire delivery position is a little high. A gap exists between the filler wire and the weld pool, allowing the droplet to grow continuously at the wire tip. When the growing droplet enters the arc column, the plasma jet pushes the droplet away from the electrode, and the droplet starts to oscillate in a front-to-back motion. The magnitude of the droplet displacement does not decrease with time, but the oscillation frequency decreases with increasing droplet size. Metal transfer takes place when the growing droplet touches the weld pool.

In P-GMA welding, metal transfer occurs in a free flight mode. In this mode a pendant metal droplet is formed and grows at the tip of the wire due to the heat from the arc, detaches and transfers to the weld pool through the arc column. After detachment, the leftover pendant liquid can oscillate in an up-
and-down motion. The magnitude of the droplet displacement reduces with time. As in interrupted cold-wire GTA welding, the frequency of the droplet oscillation decreases with increasing droplet size.

![Figure 6.1 Comparison of the weld pool in cold-wire GTA welding with an uninterrupted metal transfer (top row) and with an interrupted metal transfer (middle row), and in P-GMA welding (bottom row). The pictures show the situation before, during and after current pulses were applied.](image)

The results of the experiments on cold-wire GTA welding show that current pulses can be used to trigger weld pool oscillation effectively. During the high current period the high arc force depresses the weld pool until a balance is built up between the pressure generated by the arc and the pressure
due to surface tension and gravity. When the welding current switches back to its base level, the arc pressure reduces and the surface tension and gravity force the weld pool surface towards its equilibrium position triggering oscillation. Under welding conditions used in the experiments, the partially penetrated weld pool oscillates in a sloshy mode. This oscillation mode, as described in chapter 3, is considered as standing waves with a wavelength in the same order of magnitude as the weld pool length.

In the case of cold-wire GTA welding with interrupted bridging transfer mode, the transferred droplets can trigger weld pool oscillation. This oscillation is caused by the action of the surface tension and gravity rather than by the momentum of the droplet. The oscillation modes of the partially and fully penetrated weld pools are similar to those triggered by pulsing the current.

Weld pool oscillation frequency can be revealed by analysis of the voltage for cold-wire GTA welding, since a linear relationship exists between the arc length and the voltage. With uninterrupted bridging transfer, the voltage signals are not disturbed by the metal transfer. The liquid metal flows smoothly into the pool and does not disturb the dynamics of the weld pool and the voltage signal. The addition of filler wire in cold-wire GTA welding, however, can influence the weld penetration due to the modification of the chemical composition, and thus of the liquid flow in the weld pool. As a result, penetration sensing based on pool oscillation can be applied successfully during welding in this mode but, for the single frequency approach, welding trials are required to determine an appropriate reference frequency. The applicability of oscillation based penetration sensing is demonstrated for the case of orbital welding in chapter 4.

In the case of interrupted metal transfer, the voltage signal contains information concerning the weld pool and the pendant droplet oscillations. The implication in this case is that oscillation based penetration sensing in interrupted GTA welding is less reliable than in the uninterrupted GTA welding. To prevent the occurrence of interrupted metal transfer, the contact between the wire and the workpiece should be maintained. This can be achieved by monitoring contact between the filler wire and the workpiece, for instance by connecting the filler wire to a tactile sensing unit, and applying a feedback system to adjust the wire position.

The results of the study on P-GMA welding show several complexities with regard to monitoring liquid metal oscillation in P-GMA welding. As
discussed in chapter 5 the current pulses cannot be used to trigger weld pool oscillation for P-GMA welding under conditions used in this study. The arc pressure, which initiates weld pool oscillation in GTA welding, has a negligible effect. Reasons for the lack of direct influence of current include the use of longer arc length compared with GTA welding, the detachment of the droplet and the existence of a distributed arc root on the weld pool surface. In contrast, the impact of the transferred droplets generates travelling liquid waves with a wavelength significantly smaller than the length of the weld pool. A change in the wave behaviour between partially and fully penetrated weld pools was not observed. This can be related with the extent of the supporting solid at the root of the pool. When the width of the fully penetrated pool at its root is relatively small, the supporting solid metal will prevent liquid motion at the bottom of the pool. When this width enlarges however, the weld pool suddenly sags. The liquid dynamics become very complex and difficult to characterise. Since P-GMA weld pools do not oscillate differently in partial and full penetration conditions, application of oscillation based penetration sensing under conventional P-GMA welding is virtually impossible.

The dynamics of the P-GMA weld pool do not produce clear finger prints on the voltage. This is caused by a number of factors. The first is due to the difficulty in triggering weld pool oscillations effectively. The second is the position of the arc root on the workpiece, which is usually distributed on surface oxides at or close to the pool leading edge. This is different from the situation in GTA welding with negative electrode polarity, where electrons are emitted from the tungsten electrode towards the weld pool, and the root at the workpiece is situated on the liquid metal. Another factor that makes monitoring pool dynamics using voltage measurements in P-GMA welding difficult is the non linear relationship between the arc voltage and the total arc length.

The approach employed to assess the behaviour of the arc in this study, i.e. considering the arc column as two entities: a bright arc and a normal arc, clarifies the non linear relationship between the arc length and the voltage. This uncommon relationship is related to changes in the average electric field strength. The effect originates from evaporation of the electrode wire, the rate of which increases when the pendant droplet is more exposed to the welding arc, i.e. when the droplet grows or stretches. It is known that the presence of metal vapour leads to higher electrical conductivity and the emission coefficient of the plasma. The voltage drops with increasing conductivity but increases with increasing radiation emission coefficient. Apparently, the energy loss due to the higher emission coefficient in the bright arc region can override the energy
saving due to the higher electrical conductivity. Increasing metal evaporation rate during the growth and the oscillation of the droplet leads to a more extended bright arc region. As a result, even though the total arc length reduces, the voltage may increase. The pendant droplet oscillations in P-GMA welding leave noticeable traces on the voltage. As presented in chapter 5, this is a result not only of changes in arc length but also, and more importantly, of modification of the arc structure.

The abnormal voltage-arc length behaviour is not encountered in the case of GTA welding. The reason is that the GTA welding electrode is not consumable so that the metal evaporation rate is lower and virtually constant. Therefore, the chemical composition of the plasma and the average electrical field strength over the whole arc column can be assumed to be unchanged and the voltage is proportional to the total arc length.

The results gained from the present study help to explain several aspects of the complex structure and behaviour of welding arcs. Separating the arc column into two distinct regions yields a better relationship between the arc length and the voltage than considering the arc column as a single entity. The proposed conceptual model for arc voltage in P-GMA welding, assuming a constant voltage drop at the fall regions, confirms that the average electric field strength of the bright arc region close to the electrode is higher than that of the normal arc. Some aspects, for instance the coupling of the droplet area in contact with arc, the arc metal evaporation rate, the plasma temperature and the arc intensity require more experimental and theoretical data. In particular it would be interesting to measure the plasma temperature, the arc intensity and the chemical composition in different arc regions (i.e. the bright arc and the normal arc) over time periods in the order of a few tenths of a millisecond.

Some work is needed in order to extrapolate the results of this study to practical applications. The downward momentum of the oscillating droplet can be used to enhance droplet detachment and reduce the required current level. Using the fingerprint of droplet oscillations in the voltage for monitoring the droplet movement and applying a feedback system, the current pulse can be synchronised in such a way so that it is superimposed on the welding current when the pendant droplet moves towards the weld pool. The conceptual arc model can be developed further so that it can be of used to improve the reliability of arc sensing. One of the potential applications is for seam tracking during narrow gap welding commonly used in the manufacture of thick wall components. Voltage monitoring has been employed to control the electrode position relative to the joint side wall in order to obtain consistent weld fusion
on both groove faces. The increase of arc voltage due to arc structure modifications can be misinterpreted by the tracking system. Models can be developed so that the influence of the metal evaporation rate and arc shape on the voltage can be taken into account and the accuracy of the tracking system can be improved.

6.2 Conclusions

Based on the study presented in this thesis, the following general conclusions can be drawn.

Pendant droplet behaviour

- During P-GMA welding pendant and the detached droplets can be triggered into oscillation.
- Regardless of the welding process, pendant droplet oscillations leave traces on the voltage signals.

Weld pool behaviour

- Current pulses can be used to trigger weld pool oscillation effectively for cold-wire GTA welding but not for P-GMA welding under the conditions used in this study.
- The interactions between the transferred droplets and the weld pool can trigger the weld pool into oscillation.
- The dynamics of the weld pool in the case of cold-wire GTA and P-GMA welding manifest as standing and travelling waves respectively.
- The cold-wire GTA weld pools, under conditions used in this study, oscillate in a sloshy mode.
- In the case of uninterrupted cold-wire GTA welding, weld pool oscillation frequency can be revealed by analysis of the voltage, to a similar accuracy to that obtained for autogenous GTA welding.
- In the case of interrupted cold-wire GTA welding, the oscillation of the pendant droplet disturbs the voltage signal. Weld pool oscillation monitoring is therefore less reliable than for uninterrupted GTA welding.

- The surface motion of the P-GMA weld pool in this study cannot be monitored from the voltage.

**Arc behaviour**

- Different regions of arc columns, *i.e.* the bright arc region and the normal arc region can be identified based on the arc intensity.

- The non linear relationship between the arc voltage and the arc length in P-GMA welding is caused by modification of the arc structure.

- The modification of the arc structure, as indicated by the alteration of the bright arc region extension, is induced by changes in metal evaporation rate. An increase of metal vapour content in the plasma close to the electrode (anode) is indicated by an increased radiative intensity.

- A linear relationship between the arc voltage and the total arc length is not observed in P-GMA welding.

- A conceptual model for arc voltage, assuming a constant voltage drop at the fall regions, indicates that the average electric field strength of the bright arc region close to the electrode is approximately 1.7 V mm\(^{-1}\), higher than that of the normal arc, which is approximately 1.1 V mm\(^{-1}\).

- In the conceptual model, the voltage of different arc regions is linearly proportional to the length of each region.

- The average bright arc and normal arc electric field strengths are valid for all of the P GMA welding conditions examined.
Summary

The purpose of this research is to obtain insight into the oscillation behaviour of the liquid metal and the arc behaviour during GMA welding. Observations of the weld pool and the arc were undertaken by visual means using a high-speed video and by analysis of the voltage.

To deal with the complex phenomena that take place, the research is performed in two steps; firstly, with cold-wire GTA welding where a filler wire is introduced into the weld pool without being preheated and independent from other welding parameters, and secondly with pulsed-current GMA (P-GMA) welding where the filler wire is part of the electric circuit.

The experiments with cold-wire GTA welding were carried out on stainless steel AISI 316L tubes. The results showed that for the same penetration state the oscillation modes of the cold-wire and the autogenous GTA weld pools are similar. Under welding conditions used in this study the partially and the fully penetrated welds oscillate in a sloshy mode and frequencies can be predicted from relatively simple analytical expressions based on weld pool length rather than an equivalent weld pool diameter.

In the case cold-wire GTA welding is performed in the uninterrupted bridging transfer mode the voltage signals are not disturbed by the metal transfer. The frequency of the weld pool oscillations can be revealed from the analysis of the voltage since a linear relationship between the arc length and the voltage exists. As a result, determination of the oscillation frequency from the analysis of the voltage signals can be performed with the same accuracy as in the case of autogenous GTA welding. Experiments showed that oscillation based penetration sensing can be applied successfully with this welding mode.

The pendant droplet in the case of interrupted metal transfer can oscillate due to the action of the plasma jet. This oscillation is reflected on the voltage signals and may disturb the signals associated with weld pool oscillations. The interaction between the transferred droplets and the weld pool triggers the pool
into oscillation. Accordingly the results of voltage analysis to determine the weld pool oscillation frequency can be less accurate than those obtained in the case of autogenous GTA welding or the uninterrupted cold-wire GTA welding.

To study the liquid metal and the arc behaviour during P-GMA welding experiments are carried out with mild steel S235JR plate. The results showed that the current pulses cannot be used to trigger weld pool oscillation effectively, but the impact of the transferred metal droplets can generate travelling liquid waves on the pool. It is also found that the pendant droplet oscillates in an up-and-down motion. The magnitude of the droplet displacement reduces with time and the frequency reduces with increasing droplet size.

In P-GMA welding the dynamics of the weld pool are not reflected clearly on the voltage. In contrast, the oscillation of the pendant droplet is indicated on the voltage signals. The experiments showed that the arc can be divided into different regions based on its intensities. It is also shown that due to the growth and the oscillation of the droplet, the extent of the different arc regions changes. Apparently the modification of the arc structures (the change in the extent of different arc regions) influences the voltage, this leads to a non-linear relationship between the arc voltage and the arc length.

There is strong evidence that the modification of the arc structure is caused by the alteration of metal vapour concentration in the plasma. An increase of metal vapour content in the plasma close to the electrode (anode) is indicated by a larger bright arc region. A proposed conceptual model describes the relationship between the arc voltage and the extent of the different arc regions. Assuming a constant voltage drop at the fall regions, the model indicates that the average electric field strength of the bright arc region close to the electrode is higher than that of the normal arc. This result can be of importance for improving welding process control and through the arc sensing, for example for optimising droplet detachment to minimise spatter and reduce fume generation. The physical phenomena taking place within the different regions of the arc however require further research. This should include experimental measurements of arc composition and temperature, and the development of a mathematical model of the plasma, including energy exchange due to radiative transport and multi-component diffusion.
Samenvatting

Het doel van het in dit proefschrift beschreven onderzoek is het verkrijgen van meer inzicht in het oscillatiegedrag van het vloeibare metaal en het gedrag van de lasboog tijdens het MIG/MAG-lassen (GMA-lassen). Het gedrag van het lasbad en de boog is geobserveerd met behulp van hoge snelheid video-opnamen en door analyse van de boogspanning.

Om de complexe verschijnselen die optreden, indien toevoerdraad wordt geïntroduceerd tijdens het lassen, te ontrafelen is het onderzoek uitgevoerd in twee fasen. De eerste fase is gewijd aan het TIG-lassen met toevoerdraad, waarbij de niet-verwarmde toevoerdraad in het lasbad wordt ingebracht. De toepoersnelheid van de draad is onafhankelijk van de overige lasparameters te variëren. Vervolgens is de stap gezet naar het pulserend MIG/MAG lassen, waarbij de continu toegevoerde draad deel uitmaakt van het elektrische circuit.

De TIG lasexperimenten met koude draadaanvoer zijn uitgevoerd op buizen van roestvast staal AISI 316L. De resultaten tonen dat bij een gelijke inbranding, het oscillatiegedrag van het lasbad bij het TIG-lassen en het TIG-lassen met toevoerdraad eender is. Met de in dit onderzoek gebruikte lasparameters oscilleert het lasbad bij partiële inbranding en bij volledige doorlassing in een heen-en-weer (sloshy) oscillatiemode. De frequenties kunnen voorspeld worden met relatief eenvoudige analytische uitdrukkingen gebaseerd op de lasbadlengte.

Als bij TIG-lassen met koude draadaanvoer het materiaaltransport plaats vindt op een ononderbroken wijze, wordt het boogspanningssignaal hierdoor niet verstoord. De frequentie van de oscillatie van het lasbad kan bepaald worden uit de analyse van het spanningssignaal aangezien er een lineair verband bestaat tussen de booglengte en de spanning. Het is mogelijk de oscillatiefrequentie met eenzelfde nauwkeurigheid te bepalen als in het geval van het TIG-lassen zonder draadtoevoer. Experimenten hebben aangetoond dat penetratiecontrole gebaseerd op het oscillatiegedrag van het lasbad succesvol kan worden toegepast.
Indien het materiaaltransport plaats vindt op een onderbroken/intermitterende manier, kan de aan de toevoerdraad hangende druppel oscilleren onder invloed van de plasmastroming. Dit oscillatiegedrag van de druppel kan worden teruggevonden in het spanningssignaal en kan het signaal verstoren. De impuls van de getransporteerde druppel op het lasbad resulteert in een oscillatie van het lasbad. Uit de analyse van het spanningssignaal blijkt dat de frequentie waarmee het lasbad oscilleert minder nauwkeurig kan worden bepaald, dan in het geval van TIG-lassen zonder toevoegdraad en het TIG-lassen waarbij de draad op een ononderbroken wijze wordt toegevoerd.

De experimentele studie naar het gedrag van het vloeibare metaal en de lasboog tijdens het pulserend MIG/MAG-lassen is uitgevoerd op constructiestaal, S235JR. De resultaten lieten zien dat de stroompulsen niet in staat zijn het lasbad te laten oscilleren. De impuls van de getransporteerde druppels kunnen lopende golven in het lasbad genereren. Tevens is waargenomen dat de aan de toevoerdraad hangende druppels op-en-neer bewegen. De amplitude van deze beweging neemt af met de tijd na de stroompuls en met toenemende druppelafmeting.

Bij pulserend MIG/MAG-lassen is het dynamische gedrag van het lasbad niet duidelijk terug te vinden in het spanningssignaal. Dit in tegenstelling tot het oscillerende gedrag van de druppel, dat duidelijke sporen achterlaat. De experimenten tonen aan dat de boog kan worden ondervoldeeld in gebieden met verschillende lichtintensiteiten. Het blijkt dat door de groei en oscillatie van de druppel, deze gebieden in grootte veranderen. De verandering in boogstructuur beïnvloedt de spanning op een manier die niet voldoet aan de normale lineaire relatie tussen booglengte en boogspanning.

Er zijn sterke aanwijzingen dat de modificatie van de boogstructuur gerelateerd is aan een wisselende concentratie metaaldamp in de boog. Een verhoogde metaaldampconcentratie in de nabijheid van de elektrode uit zich in een hoge lichtintensiteit. Een conceptueel model wordt voorgesteld dat de relatie beschrijft tussen de boogspanning en de grootte van de verschillende regionen in de boog. Aannemende dat de spanningsval in de anode en kathode valgebied constant blijft, geeft het model aan dat de elektrische veldsterkte nabij de elektrodedraad hoger is dan in het geval van een ‘normale’ boog. Dit resultaat is van belang bij verbetering van de mogelijkheden voor lasprocescontrole en het gebruik van de lasboog als sensor voor het optimaliseren van druppelafspitting, waarbij spatverliezen en lasrookontwikkeling verminderd.
kunnen worden. De fysische fenomenen die in de verschillende regionen van de lasboog plaatsvinden vergen verder onderzoek. Dit onderzoek zou experimentele metingen van lasboogsamenstelling en -temperatuur moeten bevatten, gekoppeld aan de ontwikkeling van een mathematisch model voor het plasma, waarbij rekening wordt gehouden met de energie uitwisseling ten gevolge van straling en multi-componenten diffusie.
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B.Y.B. Yudodibroto, January 2010
List of publications

Journal articles:


Conference:

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