A Study of Short Circuiting Arc Welding
A Study of Short Circuiting Arc Welding

PROEFSCHRIFT

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Chapter 1

General introduction

1.1. Gas metal arc welding

1.1.1. General description

Gas metal arc welding (GMAW) is a welding process in which an electric arc burns between a continuously fed welding wire and a workpiece, for instance two metal plates which have to be joined. The situation is schematically presented in Fig. 1.1. The heat produced by the arc results in partial melting of the workpiece and melting of the tip of the electrode wire. Under the action of different forces the molten metal is transported from the electrode through the arc towards the weld pool. In this way, a weld pool is formed which after solidification results in a joint. During welding the liquid metal in the weld pool is screened from the environment by a shielding gas [1.1].

In the case of GMAW direct current is commonly used with the electrode positive. Both arc voltage and arc current depend on the arc length and are determined by the voltage-current characteristic of the arc and that of the power source used (see Fig. 1.2). The intersection of both characteristics is called the operating point.

To ignite the arc, it is necessary to stimulate local electron emission of the cathode. This is established by making short circuit contact between the electrode wire and the workpiece [1.2, 1.3]. The subsequent high short circuit current raises the temperature of the metal and thus enables thermionic electron emission. Immediately after the short circuit is broken, the arc is ignited.
The voltage distribution over the arc is not linear but shows large deviations from linearity near the anode and the cathode. In view of this, the arc can be divided into three zones: the anode fall region, the arc column and the cathode fall region. The non-linearity of the voltage plays an important role in the heat generation in the different zones [1.4].

**Fig. 1.1** Schematic presentation of GMAW.

**Fig. 1.2** Current - voltage characteristic of arc and power source [1.5].
A large number of parameters influences the gas metal arc welding process, such as:
- arc length,
- voltage,
- current, wire feed rate,
- travel speed,
- contact tube to workpiece distance (CTWD),
- electrode diameter,
- electrode position,
- welding position,
- polarity,
- shielding gas composition.

The most important parameters of the GMA welding process are voltage and current, their product being equal to the generated power.

As an illustration Fig. 1.3 shows the influence of the power on the weld bead appearance.

Fig. 1.3  Weld bead appearance of weld produced with a) low power, b) intermediate power and c) high power; workpiece dimensions 50 x 270 mm.
Figure 1.3a represents a weld bead, produced with low power (low voltage and low current). Figures 1.3b and 1.3c show a weld made with intermediate power (high voltage and low current) and with high power (high voltage and high current), respectively. As can be seen, these welding parameters influence the weld bead significantly.

1.1.2. Heat transfer during gas metal arc welding

During the GMA welding process heat is produced in the arc and by Joule heating in the electrode extension.

Heating of the electrode wire (anode)
Part of the heat produced in the arc is transferred to the tip of the electrode wire. This anodic arc heat consists of the heat received from the arc column by radiation, the heat generated in the anode fall region, the heat due to the capture of electrons by the anode and the thermal energy of the electrons (due to the temperature difference between the arc column and the anode). Furthermore, heat is generated by Joule heating in the electrode extension. Joule heating depends on the electrical resistivity of the electrode material, the electrode extension, the cross section area of the electrode and the current. It should be noticed that the electrical resistivity is temperature dependent and increases along the electrode extension.
Both arc heating and Joule heating contribute to melting of the electrode wire. During welding the melting rate of the wire should be equal to the wire feed rate in order to maintain a stationary situation. The heat collected in the electrode wire is transferred to the weld pool by metal transport.

Heating of the workpiece (cathode)
The heat transferred to the workpiece by metal transport, together with the heat received from the arc (cathodic arc heating) determine the shape and dimensions of the weld pool.
The cathodic arc heat includes the heat acquired from the arc column, the heat generated in the cathode fall region, the heat required to emit electrons from the cathode and the heat necessary to elevate the electrons from the temperature of the cathode to the arc column temperature.
The Joule heat, generated in the workpiece is commonly neglected, as the current density in the workpiece is low.
Although heat transport is dealt with in detail in chapter 3, the following important parameters relevant to the heat transport should already be mentioned.

- Process efficiency.
  This quantity represents the fraction of the total supplied power (the product of voltage (U) and current (I)) dissipated in the anode and cathode [1.6]. For welding with a consumable electrode the process efficiency is given by:

\[
\eta_p = \frac{Q_{a-an} + Q_{a-c} + Q_r}{UI} \cdot 100\% 
\]  

(1.1)

Q_{a-an} and Q_{a-c} represent the energy supplied per unit time by the arc for heating the anode and cathode respectively. Q_r stands for the Joule heating of the anode per unit time. For GMAW the process efficiency is about 60 to 90 % [1.5].

- Melting efficiency.
  The melting efficiency is defined as the fraction of the net energy input which is actually used for heating and melting the metal. This can be expressed by the following equation:

\[
\eta_m = \frac{Q A_w v \rho_s}{UI} 
\]

(1.2)

with Q the heat required to raise a unit volume of metal from room temperature to the melting point and melt it, A_w the transverse cross sectional area of the weld, v the travel speed and \( \rho_s \) the density of the solid metal. The product of voltage (U) and current (I) gives the total supplied power. For GMAW \( \eta_m \) is approximately 30 to 50 % [1.5].

- Heat input.
  The heat input is defined as the amount of heat which enters the workpiece per unit length of weld. The heat input can be expressed by the following equation:

\[
H = \eta_p \cdot \frac{UI}{v} 
\]

(1.3)

with U the arc voltage, I the welding current, v the travel speed and \( \eta_p \) the process efficiency. The heat input is an important quantity as it determines both the peak temperature and the cooling rate of the material and, hence, the subsequent (metallographic) microstructure and the dimensions of the heat affected zone.
1.1.3. Metal transfer during gas metal arc welding

Closely related to the heat transport is the transport of metal during the welding process. Gas metal arc welding is accompanied by the transport of liquid metal from the electrode to the weld pool. Observation by means of high-speed filming and the use of oscillographic techniques reveal the existence of several types of metal transport. The mode in which metal transfer occurs, has a large effect on weld pool metallurgy, influencing penetration, solidification, heat flow and mass input [1.7]. The different modes of metal transport are classified according to phenomenological features by the International Institute of Welding (I.I.W.) [1.8]. Metal transport during arc welding is divided into three major modes:

1) free flight transfer,
2) bridging transfer,
3) slag protected transfer.

These modes can be sub-divided into a number of transfer types, listed in table 1.1. A schematical presentation is given in Fig. 1.4.

![Diagram of metal transfer modes](image)

*Fig. 1.4 Types of metal transfer [1.4].*
Table 1.1  Classification of metal transfer [1.8].

<table>
<thead>
<tr>
<th>designation of transfer type</th>
<th>welding process (examples)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Free flight transfer</td>
<td>MIG welding</td>
</tr>
<tr>
<td>1.1 Globular transfer</td>
<td>MAG welding with CO₂</td>
</tr>
<tr>
<td>1.1.1 Drop transfer</td>
<td>MAG welding, MAG welding</td>
</tr>
<tr>
<td>1.1.2 Repelled transfer</td>
<td>with gas mixtures</td>
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<td>1.2 Spray transfer</td>
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</tr>
<tr>
<td>1.2.1 Projected transfer</td>
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<tr>
<td>1.2.2 Streaming transfer</td>
<td>MAG welding with gas</td>
</tr>
<tr>
<td>1.2.3 Rotating transfer</td>
<td>mixtures</td>
</tr>
<tr>
<td>1.3 Explosive transfer</td>
<td>Plasma-MIG welding, MIG</td>
</tr>
<tr>
<td></td>
<td>and MAG welding with high</td>
</tr>
<tr>
<td></td>
<td>current density</td>
</tr>
<tr>
<td>2. Bridging transfer</td>
<td>Metal arc welding</td>
</tr>
<tr>
<td>2.1 Short-circuiting transfer</td>
<td>MAG welding with short arc</td>
</tr>
<tr>
<td>2.2 Bridging transfer without</td>
<td>process</td>
</tr>
<tr>
<td>interruption</td>
<td>Welding with cold or hot</td>
</tr>
<tr>
<td></td>
<td>wire additions</td>
</tr>
<tr>
<td>3. Slag-protected transfer</td>
<td>Submerged arc welding</td>
</tr>
<tr>
<td>3.1 Flux-wall guided transfer</td>
<td>Metal arc, electro slag,</td>
</tr>
<tr>
<td>3.2 Other modes</td>
<td>cored wire</td>
</tr>
</tbody>
</table>

The type of mode that will occur under a specific set of conditions depends on the forces involved in the metal transfer process, which in turn depend on the welding parameters. The following forces play a role in metal transfer during welding.

- Gravitational force.

This force is proportional to the mass of the liquid drop and acts as a detaching force when welding in the horizontal position. An approximation of the gravitational force is given by the equation:

\[
F_g = \frac{4}{3} \pi r^3 \rho g
\]  

(1.4)
in which \( r \) is the droplet radius, \( \rho \) the density of the liquid drop metal and \( g \) the gravitational constant.

- Lorentz force.
  
  This force is often referred to as electro-magnetic pinch force and results from the interaction between the diverging or converging current flow in the electrode and the current induced magnetic field. The Lorentz force can be expressed by the equation:

\[
F_{em} = \bar{J} \times \bar{B}
\]  

(1.5)

with \( J \) the current density and \( B \) the induced magnetic field strength.

The Lorentz force is proportional to the square of the current and can be approximated by:

\[
F_{em} = \frac{\mu_0 I^2}{4\pi} \cdot \chi
\]  

(1.6)

with \( \mu_0 \) the magnetic permeability of vacuum, \( I \) the current and \( \chi \) a geometric factor, dependent on the droplet radius, the electrode radius and the contact angle between plasma and droplet. In the case of a diverging current distribution, the radial inward directed component of the Lorentz force pinches off the droplets [1.9, 1.10].

- Entrainment drag due to shielding gas flow and plasma/vapour jet.

This is a minor force during detachment but is responsible for the acceleration of the droplets observed during transfer to the weld pool [1.10, 1.11].

- Surface tension.

The surface tension force aspires after a minimal surface energy. In that way it acts in general as a droplet detachment counteracting force. However, in the case of bridging transfer the surface tension promotes metal transfer during the final stage of the short circuit period. The surface tension force acting on the droplet can be represented by:

\[
F_\gamma = 2\pi r \gamma
\]  

(1.7)

in which \( r \) is the electrode radius and \( \gamma \) the temperature dependent surface tension of the liquid metal [1.10].

- Explosive forces.

These forces are due to the eruption of gas from the liquid metal. In the case of steel the main chemical reaction responsible for gas eruptions is the burn-off of carbon. The explosive forces are responsible for non-axial metal transport.
Droplet transfer is commonly envisaged as being due to a balance of the static forces mentioned above. In each type of metal transfer a dominant force can be assigned, but frequently detachment force is a combination of several forces. This is illustrated in Fig. 1.5 where the forces are given as function of the welding current. As can be seen, the electro-magnetic force plays an important role for high values of current, while in this current range the drag force and the gravitational force become less influential.

Another approach to model the metal transfer during arc welding is based on the theory of Rayleigh instability. This theory describes the break down of a long cylindrical column of liquid into drops due to perturbations as a result of the influence of the electro-magnetic force [1.4]. The theory, however, is limited to specific circumstances and can hardly be applied in the case of arc welding, as a cylinder of liquid only exists during streaming transfer at high current levels. In line with this Eagar [1.13], in his iconoclastic view of the physics of welding, states that the static force balance theory is by far the more appropriate one.

![Diagram](image_url)

**Fig. 1.5** The forces acting on the droplet at a steel electrode tip during arc welding as a function of current [1.12]. $F_Y =$ surface tension force, $F_{em} =$ electro-magnetic force, $F_d =$ drag force, $F_g =$ gravitational force.
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Free flight metal transfer is observed when the voltage is relatively high. The transport of liquid metal occurs as distinct droplets without contact between electrode and weld pool. The subdivision of transfer types is classified by the size of the droplets. For instance, when the welding current is increased at a constant value of the arc voltage a transition from drop transfer to spray transfer can be observed. This occurs at a critical current level (transition current) and is accompanied by an abrupt increase in droplet frequency and a decrease in droplet size. When the current is further increased tapering of the electrode tip is observed and metal transport starts to take place as a continuous stream of very small droplets.

A remarkable type of droplet transfer, which is observed frequently during arc welding with CO₂ gas shielding, is the so-called repelled transfer. The droplet is pushed upwards and sideways, as a consequence of a droplet detachment counteracting electro-magnetic pinch force, due to the small constricted area of contact between the arc and the droplet (converging current). The droplet size is relatively large and detachment finally occurs under the action of gravity. Repelled transport is a non-axial or deflected type of metal transport.

A different mode of metal transfer, that is encountered in the low voltage - low current (wire feed rate) region, is short circuiting transfer or dip transfer. In this mode the electrode wire contacts the weld pool regularly. During this contact period liquid metal is transferred by gravity, electro-magnetic pinching and surface tension forces.

Figure 1.6 depicts schematically the types of metal transfer during GMAW as a function of voltage and wire feed rate (current). In the high voltage range free flight transfer is encountered, while at low voltage and low wire feed rate, short circuiting transfer takes place. When the wire feed rate (current) level becomes too high in the low voltage range, the electrode wire will be pushed against the bottom of the weld pool, making welding impossible. This phenomenon is called stubbing.

1.1.4. Flow in the weld pool

It is well known that during arc welding flow occurs in the weld pool. This flow is of importance, as it influences the weld pool geometry and, hence, the structure of the weld metal. The effect of weld pool flow is schematically depicted in Fig. 1.7.
General Introduction

Fig. 1.6 Types of metal transfer during GMAW as function of wire feed rate and voltage.

Fig. 1.7 Flow in the weld pool: a) radially outward, b) radially inward [1.5].
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Flow in the weld pool is caused by:

- electro-magnetic forces resulting from the diverging electrical current in the weld pool. The resulting pressure differences generate a flow towards the centre of the weld pool (Lorentz flow), as a consequence of which a relatively small and deep weld pool will be formed, see Fig. 1.7, type b;
- variations in surface tension along the surface of the weld pool, due to temperature gradients or gradients in solute content (especially surface active elements, such as sulphur and oxygen), resulting in weld pool flow of type a or type b (Marangoni flow);
- variations in liquid density due to temperature gradients in the weld pool (type a);
- the drag forces induced by streaming of the shielding gas, plasma and vapour jets along the surface of the weld pool in an outward direction (type a);
- the momentum of droplets entering the weld pool, in the case that filler metal is used (type b) [1.14].

In addition to the weld pool flow, oscillations can also occur in the weld pool [1.15, 1.16]. These oscillations play an important role during short circuiting arc welding as they are strongly related to process stability. In chapter 6 this is dealt with in detail.

1.1.5. Methods for studying gas metal arc welding

In this section the various methods available for studying the gas metal arc welding process are briefly described. In literature several methods are mentioned which can be used to collect data on GMA welding. They are mainly used to determine the modes of metal transport. On the basis of the interpretation of the data obtained a distinction between globular, spray and short circuit transfer can be made.

In most cases use is made of collecting voltage and current data and related quantities like supplied power and electrical resistance [1.17-1.22]. The Fourier transform of current data, signal standard deviation or amplitude histograms give information about the type of transfer. It appears that none of the mentioned measuring methods is suitable in the whole range of transfer types. As stated by Liu et al. [1.23] it appears that within certain regions of the voltage-current diagram several modes of metal transfer will operate simultaneously. Table 1.2 shows the relative sensitivity of the control parameters which can be used as selection criteria to find the appropriate method. It should be noted however, within the region of short circuiting arc welding no distinction is made between optimal and non-optimal process conditions.
Table 1.2  Relative sensitivity of the control parameters for different transfer modes. H = high sensitivity, M = medium sensitivity, L = low sensitivity [1.21].

<table>
<thead>
<tr>
<th></th>
<th>short circuiting</th>
<th>transition</th>
<th>globular</th>
<th>transition</th>
<th>spray</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fourier transform</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>L</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>Peak ratios</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>Integrated amplitude</td>
<td>H</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
</tbody>
</table>

Figure 1.8 displays the voltage and current as function of time for globular, spray and short circuit transfer. Variations in current and voltage diminish as current is increased from the globular to the spray transfer situation, due to the decrease in droplet size. During short circuiting arc welding voltage and current swap between the arc and the short circuit voltage and current levels.

Another possibility of obtaining information about the features of the GMA welding process, in particular the metal transfer, is to collect and analyse acoustic/audio emission signals [1.7, 1.21, 1.22, 1.24-1.26]. The various types of metal transfer give rise to a different noise patron. Globular transfer makes a low frequency buzzing sound, spray transfer is characterised by a hissing sound, whereas during short circuit transfer the breaking up of the liquid bridge will emit a cracking sound. In fact, this acoustic approach is used in practice, as the human ear is a very sensitive instrument. Especially in the case of short circuiting arc welding, the sound frequency can be used for fine tuning of the welding parameters. Figure 1.9 shows the acoustic and voltage signals collected during short circuiting welding for three values of the wire feed rate. The figure in the middle corresponds with optimal welding conditions.

Besides high-speed filming, other possibilities of optical analysis of the process can be provided by infra-red techniques [1.25-1.27].

A good insight in the phenomena occurring during the short circuiting process can also be obtained by linking voltage and current data with data obtained by high-speed filming [1.28-1.30].
Fig. 1.8  Current and voltage as function of time for a) short circuit transfer, b) globular transfer and c) spray transfer.
Fig. 1.9  Acoustic signals (solid line) and voltage signals (broken line) as function of time for three values of wire feed rate in the case of short circuiting arc welding: a) low wire feed rate, b) optimal wire feed rate, c) high wire feed rate.
1.2. History of gas metal arc welding

GMA welding was introduced in the early 1950s. Up to that moment manual metal arc (MMA) welding was the most commonly used arc welding technique. The main advantages of the new process were the use of a continuously fed bare electrode wire, a high current density and the inert gas shielding of the arc (no slag and fume), resulting in an increased efficiency. Its primary application was welding aluminium. Further developments include operation at low current densities, the use of a broader scale of metals and the use of reactive shielding gases. GMA welding can also be designated as MIG (metal inert gas) or MAG (metal active gas) welding, depending on the nature of the shielding gas used.

During the introduction of the GMAW process problems occurred undermining its applicability. For instance, the use of pure argon as shielding gas did not result in an entirely stable arc. Steady development in the field of hardware (power source design [1.31-1.37]), shielding gas mixtures [1.38, 1.39] and consumables [1.40-1.44], during the 1960s and 1970s allowed the use of GMA welding to take over the position of MMA welding, see Fig. 1.10 [1.45]. This trend continued in recent years [1.46] with new developments of GMAW such as: short circuiting arc welding [1.47-1.49], pulse and synergic GMA welding [1.50-1.59], process control systems [1.29, 1.60-1.63], flux (metal) cored welding wires (FCW) [1.64-1.68], robotic welding [1.69-1.71] and the introduction of neural networks to obtain optimal welding parameters [1.61, 1.72, 1.73]. According to McKeown [1.45] further major developments of the process are limited and must be found in detail improvements. It seems therefore unlikely that the pace of innovation of the last decades will continue.

The development of fundamental research in the field of GMA welding started with the characterisation of metal transport [1.8, 1.11, 1.74-1.81]. In a later stage, modelling of process features (f.i. metal transport in the weld pool [1.82], heat transport [1.82-1.85]) became hot topics. More recently, the attention is focussed on process control and on methods to monitor and regulate the process.

For short circuiting arc welding or dip transfer welding, the development started in the early 1960s. In the case of short circuiting arc welding, metal is transferred from the electrode to the weld pool during the period of contact. Short circuiting arc welding is performed with low values of current and voltage. Due to the relatively low heat input the process is useful for welding thin sections, bridging root gaps, positional welding and for welding heat sensitive metals. One of the disadvantages of short circuiting arc welding is still the occurrence of spatter and lack of fusion.
Research in the field of the short circuiting arc welding process is limited. The work of Smith [1.86, 1.87] can be seen as the starting point of a more fundamental oriented approach to the short circuiting arc welding process. Later work was focussed on breaking of liquid bridges [1.9, 1.88] and the formation of spatter [1.89, 1.90]. Furthermore, efforts were made to accomplish spatter reduction by intervening in the process sequence [1.91]. This was done mainly by improvements in power source design [1.85, 1.92-1.94].

Smartt [1.95] states that GMAW should be viewed as a globally deterministic locally chaotic process. This is especially true for short circuiting arc welding.
1.3. Goal and outline of the thesis

In spite of the fact that over the years a considerable amount of information has been obtained about the short circuiting arc welding process, numerous aspects of the process are still not well understood or even misinterpreted.

The goal of this thesis is to obtain insight in the fundamentals of the short circuiting arc welding process. This will ultimately lead to the possibility of predicting the process behaviour within a wide range of process conditions.

The outline of the thesis is as follows.

The short circuiting arc welding process is described in a detailed way in chapter 2. In this chapter the experimental set-up, the measuring techniques and the procedures of data acquisition are given. Also, the most important parameters (i.e. arc time, short circuit time and short circuit frequency) are introduced. These parameters return in all following chapters of the thesis.

Chapter 3 deals with the measurements and with modelling of heat transport during short circuiting arc welding. Heat transport is an important phenomenon as it influences the melting rate of the electrode wire, the formation and the temperature of the weld pool and the heat affected zone (HAZ), and the adhesion of spatter to workpiece and gas nozzle. By means of calorimetric experiments information about heat transport is obtained and the process and melting efficiencies are determined.

In chapter 4 the attention is focussed on metal transport. Arc time, short circuit time and short circuit frequency are linked to the amount of liquid metal transferred during a short circuit cycle for different process variables, such as wire feed rate and voltage. Furthermore, spatter formation and the results of spatter loss measurements are discussed.

Chapter 5 deals with the stability of the short circuiting GMA welding process. Process stability can be quantified in a number of ways. For instance, by the standard deviation in short circuit frequency or the amount of spatter loss. The distribution (spectra) of a number of parameters is analysed, to gather a better insight into the stability of the process.

It appears that weld pool oscillations play an important role in the stability of the process. This matter is dealt with in chapter 6. It is found that surface tension, density of the liquid metal, weld pool dimensions and the mode of oscillation of the weld pool determine the oscillation frequency. A hypothesis is set up coupling the short circuit frequency with the oscillation frequency of the weld pool and the process stability. To test this hypothesis experiments are carried out under various arc welding circumstances.
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Chapter 1


Chapter 2

General features of the short circuiting gas metal arc welding process

2.1. Introduction

This chapter deals with the general features of short circuiting arc welding of mild steel. As already mentioned in the previous chapter, short circuiting arc welding is characterised by a regular contact between the electrode and the workpiece. During this contact period, metal transfer from electrode to workpiece takes place. As the arc is extinguished in the short circuit period, the heat generated by the arc is absent which implies that the overall heat input, compared to open arc welding, is low. Therefore, short circuiting arc welding always results in a small fast freezing weld pool and, hence, is especially suited for joining thin sections, out of position welding and bridging root openings.

The short circuiting arc welding process can be appropriately described in terms of voltage and current data as function of time. During the arc period the arc burns between the electrode and the weld pool and a droplet of liquid metal is formed at the end of the electrode. In this time interval the arc length decreases continuously until the droplet at the end of the electrode touches the weld pool and a bridge of liquid metal is formed between the electrode and the weld pool. At the moment contact is established, the arc is extinguished and the current rises rapidly, whereas the voltage drops to a low level. This marks the beginning of the short circuit period. Due to the high short circuit current and the subsequent high Lorentz force, necking of the liquid bridge starts to occur. The short circuit period ends by rupture of the liquid bridge and the reignition
of the arc. After reignition the whole cycle is repeated. This periodicity is also encountered in
the dissipated power and the electrical resistance of the arc-wire system as a function of time.
The different stages of the process can be depicted in a voltage-current diagram, an example
of which is given in Fig. 2.1. In this figure the direction of the operating point is counter-
clockwise. It can be seen that during short circuiting arc welding a stable situation does not
occur, because the arc length related to voltage and current changes continuously. For
comparison, the situation for globular and spray transfer is also depicted in Fig. 2.1.

![Voltage-current diagram for GMAW](image)

*Fig. 2.1 Voltage-current diagram for GMAW.*
2.1.1. Heat transport during short circuiting gas metal arc welding

Heat transfer during short circuiting arc welding is somewhat different from that during open arc welding due to the alternating presence of the arc. In the case of short circuiting GMA welding heat is generated in the arc and in the electrode extension (Joule heating) during the arc period, while during the short circuit period Joule heating is the only energy source.

A small volume of the electrode wire passing from the contact tube to the arc experiences a number of short circuit periods and arc periods before it reaches the arc zone. During these short circuit cycles the volume element is subject to Joule heating. The Joule heating is cyclic as the current through the electrode changes between the arc current and the short circuit current. Eventually, the volume element contacts the arc after which arc heat is added and melting starts to occur. During the final short circuit, Joule heating becomes very intense as necking of the part of the wire starts to occur, increasing the current density, while the electrical resistivity due to the increased temperature is also raised.

It should be noted that during short circuiting arc welding a non-equilibrium situation exists. The melting rate of the wire can be divided into the melting rate during the arc period and the melting rate during the period of short circuit. During the arc period the wire feed rate exceeds the melting rate of the electrode and the electrode with the growing pendant drop approaches the weld pool. In the short circuit period metal is transferred to the electrode at a rate which is larger than the wire feed rate. This results in the formation of the arc gap, immediately followed by arc reignition. Thus, the position of the solid-liquid interface shifts continuously, indicating the non-equilibrium situation [2.1, 2.2], see Fig. 2.2. The overall mass transport demands that under stationary conditions the wire feed rate is equal to the melting rate.

![Diagram showing shifting of the solid-liquid interface during a short circuit cycle](image)

*Fig. 2.2* Shifting of the solid-liquid interface during a short circuit cycle [2.2].
2.1.2. Metal transport during short circuiting gas metal arc welding

As stated in the introduction, metal transfer during short circuiting arc welding occurs in the period of contact between the electrode and the weld pool. In the arc period droplet growth takes place and the electrode and pendant droplet are transported towards the weld pool. When contact is established the short circuit period starts and a liquid bridge is formed. This bridge is gradually constricted mainly as a result of the radial (inward directed) component of the electro-magnetic pinch force which is proportional to the square of the current. Finally, the bridge is ruptured and the arc is reignited. This cycle is repeated in a more or less regular way [2.3].

Kiyohara et al. [2.4] modelled the metal transport in the case of short circuiting arc welding. In his model a distinction is made between:

• droplet detachment before contact occurs (free flight transfer); the droplet has the opportunity to grow to a considerable size and detaches mainly under the action of the gravitational force;

• the formation of a liquid bridge; depending on the length and diameter, as well as the current level, this bridge can either be stable or unstable: a stable bridge is associated with stubbing, while an unstable liquid bridge results in undisturbed metal transport.

At the moment of rupture, metal is transferred to the weld pool. The amount of transported metal during a short circuit period can be calculated from the wire feed rate and the short circuit frequency.

An undesirable side effect of a forceful rupture of the liquid bridge is the formation of spatter. Spatter is defined as liquid metal originating from the electrode wire which does not enter the weld pool or weld pool metal which is ejected from the weld pool. The occurrence of spatter is associated with instabilities during the process (see next section and chapter 4).
2.1.3. Irregularities during the short circuiting gas metal arc welding process

Compared to the free flight transfer mode, short circuiting arc welding is a much more dynamic welding process. This dynamic behaviour leads to an increased possibility of the occurrence of irregularities. During short circuiting arc welding three phenomena disturbing the course of the process are frequently mentioned [2.5]. These phenomena are reflected in the voltage (or current) versus time curves or can be observed with the help of high-speed filming.

The first phenomenon is the occurrence of instantaneous short circuits. The electrode touches the weld pool for a very short period of time, but no metal transport takes place. Instead, the droplet is lifted again, probably due to the high surface tension and a counteracting electro-magnetic force [2.6-2.9] and this results in extended arc periods and excessive droplet growth [2.7, 2.10-2.12]. No agreement exists about the duration of an instantaneous short circuit. Commonly accepted values of the duration range from 50 to 300 μs, but also a value of 1.5 ms is found in literature [2.5]. The occurrence of instantaneous short circuits are sometimes used as a measure of the stability of the process in the form of the instantaneous short circuit ratio [2.5]. Figure 2.3 illustrates the occurrence of instantaneous short circuits.

Another phenomenon which may give rise to problems is the failure of arc reignition [2.13]. This is observed when the wire feed rate is high and stubbing of the electrode in the weld pool occurs. Excessive forces create a large gap between the electrode and the weld pool making, reignition of the arc impossible. The welding current is zero and the voltage returns to open voltage level of the power supply. After a second short circuit the arc is ignited. This phenomenon is depicted in Fig. 2.4.

A third problem is related to wire feed rate variations. A sudden change in wire feed rate leads to a change in arc length and thus to a change in arc voltage. Wire feed rate variations are often caused by wire transport problems in the wire feed unit and the contact tube. Wear and accumulated dirt are responsible for this type of irregularity [2.14-2.17]. Wire feed rate variations are common during free flight transfer, especially when the duty cycle is high and the temperature of the contact tube is elevated due to the high current density. In the case of short circuiting arc welding, the adhesion of spatter on the contact tube also causes severe transport problems.

Although some of the problems mentioned in the foregoing can be solved or minimised by proper parameter settings, a number of problematic phenomena is still persistent and not completely understood. For instance, the fact that the regularity of the process decreases (and spatter loss increases) when lowering the wire feed rate can not be explained properly.
Therefore, the instability of the short circuiting arc welding process remains an important problem and the formation of spatter still is a main disadvantage of the process.

![Graph](image)

**Fig. 2.3** Unfiltered and filtered voltage data as function of time. The unfiltered data show instantaneous short circuits.

![Graph](image)

**Fig. 2.4** Filtered current and voltage data as function of time, showing the failure of arc reignition.
2.2. Experimental

2.2.1. Experimental set-up

To obtain detailed information about the general features of the short circuiting GMA welding process, a large number of experiments was carried out under different welding conditions.

The welding equipment used consisted of a constant voltage transistorised power source (Welding Institute Transistor 500). With the power source it was possible to vary the slope of the voltage-current characteristic and the induction of the electrical circuit. With respect to the slope/impedance of the power source the following remark should be made.

The rise rate of the short circuit current depends on the impedance (choke) in the electric circuit [2.12, 2.18, 2.19]. In fact, the current rises exponentially to a peak value. After reignition of the arc the current level decreases exponentially to the arc current level.

The maximum reachable current level is limited by the slope of the power source characteristic (static characteristic). The slope is equivalent to an impedance, but is customarily defined as the voltage drop per 100 A of current rise [2.20, 2.21].

The electrode wire was supplied by a wire feed unit. It should be noted that the relationship between current and wire feed rate is not linear. The wire feed rate equals the melting rate of the electrode, which includes a term due to arc heating directly proportional to the current and a term corresponding with Joule heating of the electrode proportional to the square of the current.

For high values of wire feed rate stubbing of the electrode wire in the weld pool and failure of arc reignition may happen. In that case, the average current decreases sharply, and the relationship between the average current and the wire feed rate is not useful anymore. In chapter 3 more attention will be paid to the relationship between the current and the melting rate.

Welding was carried out using a water cooled welding torch with a standard contact tube, mounted directly underneath the wire drive perpendicular to the workpiece surface. In this way wire feed variations were kept at a minimum. During welding the workpiece was traversed automatically underneath the fixed torch. A schematic representation of the experimental set-up is given in Fig. 2.5.
During the experiments the current was measured by means of a transfo-shunt, while the voltage was measured between the torch (contact tube) and the workpiece. RMS current and voltage readings were displayed on a welding monitor, making it possible to select proper current and voltage settings during welding. The obtained data were recorded continuously during welding on a x-t recorder (Kipp & Zn, BD 9). Furthermore, momentary values of current and voltage were recorded by means of a transient wave form recorder (Nicolet 410) and stored on floppy disc. The data were analysed off-line (see section 2.2.2).

The wire feed rate was recorded by means of a Strunk Messmatik H5/1 wire feed measuring device. This device measures the length of the supplied wire and the welding time.

High-speed films (Hicam K20S4W, 4000 frames per second, Xenon back lighting technique to overcome the arc light) were made to observe the metal transport.

The welding parameters used are listed in Table 2.1.

![Diagram of welding setup]  
*Fig. 2.5 Schematic representation of the experimental set-up.*
Table 2.1  Welding parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>voltage</td>
<td>14 - 22 V</td>
</tr>
<tr>
<td>current</td>
<td>50 - 250 A</td>
</tr>
<tr>
<td>wire feed rate</td>
<td>25 - 300 mm/s</td>
</tr>
<tr>
<td>travel speed</td>
<td>5 mm/s</td>
</tr>
<tr>
<td>slope power source</td>
<td>-1V/100A</td>
</tr>
<tr>
<td>electrode wire</td>
<td>1.0 mm SG2, mild steel</td>
</tr>
<tr>
<td>shielding gas</td>
<td>85% Ar - 15% CO₂</td>
</tr>
<tr>
<td>gas flow rate</td>
<td>16 l/min</td>
</tr>
<tr>
<td>contact-tube-to-work-distance</td>
<td>20 mm</td>
</tr>
</tbody>
</table>

2.2.2. Data analysis

The current and voltage data collected by means of a transient wave form recorder (Nicolet 410) were recorded with a sampling frequency of 10 kHz and a measuring time of 400 ms. This provides a reasonable choice between either high resolution (high acquisition rate) or a good statistical sample of the repetitive signals associated with short circuit transfer (long acquisition time). The data were stored on floppy disk and off-line analysed using a personal computer. The data acquisition program consisted of a module to convert the Nicolet format into ASCII data. This was followed by a median filter (signal smoothing). The purpose of filtering the signal was to remove the influence of instantaneous short circuits.

By means of a signal analysis program (LabVIEW, National Instruments) the following parameters were obtained:

- short circuit frequency (the number of short circuits per unit time),
- average current,
- average short circuit current and arc current,
- minimum current and maximum current,
- average voltage,
- average short circuit voltage and arc voltage,
- minimum voltage and maximum voltage,
- average power,
- average short circuit power and arc power,
- minimum power and maximum power,
Chapter 2

- the distribution of and the standard deviations in these parameters.
The program distinguishes between short circuit periods and arc periods by introducing a threshold voltage drop of 8V for the start of the short circuit as suggested by Liu [2.22]. The end of the short circuit is determined by an abrupt increase in voltage, characteristic for arc reignition.

2.2.3. Materials

Bead-on-plate welds were deposited on mild steel plates (Fe 360), having a thickness of 10 mm. The chemical composition of the steel is listed in Table 2.2. The elements C, S and O are determined by Ströhlein gas analysis, while the other elements are measured by X-ray fluorescence spectroscopy (XRF), Philips PW 1480.

<table>
<thead>
<tr>
<th>element (%)</th>
<th>Mn</th>
<th>Si</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>S</th>
<th>P</th>
<th>O</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe 360 (10 mm)</td>
<td>0.72</td>
<td>0.26</td>
<td>0.02</td>
<td>0.02</td>
<td>0.10</td>
<td>&lt;0.01</td>
<td>0.014</td>
<td>0.020</td>
<td>0.0112</td>
<td>0.14</td>
</tr>
</tbody>
</table>

A copper coated mild steel solid welding wire (SG2) with a diameter of 1.0 mm was used as consumable electrode wire. The electrode wire was connected to the positive pole (DCEP) of the power source. The chemical composition of the wire is listed in Table 2.3. The elements C, S and O are determined by Ströhlein gas analysis, while the other elements are measured with the help of inductive coupled plasma optical emission spectroscopy (ICP-OES), Perkin-Elmer Plasma 2000 and 400.

<table>
<thead>
<tr>
<th>element (%)</th>
<th>Mn</th>
<th>Si</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>S</th>
<th>O</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG2</td>
<td>1.44</td>
<td>1.25</td>
<td>0.11</td>
<td>0.017</td>
<td>0.022</td>
<td>&lt;0.013</td>
<td>0.011</td>
<td>0.0084</td>
<td>0.079</td>
</tr>
</tbody>
</table>

85%Ar-15%CO2 was used as shielding gas. The gas flow rate was 16 l/min.
2.2.4. Experimental procedure

To investigate the general features of the short circuiting GMA welding process, bead-on-plate welding experiments were carried out on 10 mm thick mild steel (Fe360) plates using 85% Ar-15% CO₂ as gas shielding. The welding experiments were carried out in the short circuit mode using voltage - current combinations in the range of 14 to 22 V and 50 to 250 A respectively, corresponding with a wire feed rate in the range of 25 to 300 mm/s. The travel speed was 5 mm/s, unless mentioned otherwise. In all cases a partially penetrated weld pool was formed. Figure 2.6 shows the relationship between the average current and the wire feed rate. It can be seen that for low values of the wire feed rate, as used during short circuiting arc welding, the relationship is almost linear.

During a representative part of the experiments the voltage and the current were recorded (by means of a transient wave form recorder) and from the recorded data the various process parameters were obtained.

Each welding experiment was repeated three times under identical conditions and the obtained results were averaged.

![Graph showing relationship between average current and wire feed rate.](image)

*Fig. 2.6 Relationship between average current and wire feed rate.*
2.3. Results and discussion

2.3.1. Droplet transfer sequence

Analysis of the high-speed film pictures provides quantitative information about the course of events of droplet transport during the short circuit period. Figure 2.7 depicts the measured dimensions of the droplet diameter and the minimum bridge diameter as function of the short circuit time for optimal welding conditions. The sequence of necking of the liquid bridge is also shown in a number of pictures, taken from high-speed films, see Fig. 2.8.

Figures 2.7 and 2.8 reveal that just after the first contact with the weld pool, the droplet has a diameter of approximately 1.4 times the diameter of the electrode. The capillary action and gravity provide the possibility of transport of liquid metal towards the weld pool and the droplet shape modifies to a liquid cylinder. From that moment on necking of the liquid bridge starts to occur due the electro-magnetic pinch force (the current rises exponentially with time and the pinch force becomes increasingly important). After a certain time rupture of the liquid bridge takes place, followed by arc reignition.

The situation changes for both low wire feed rates (near open arc welding) and high wire feed rates (stubbing). In the low wire feed region the droplet can grow to a considerable size before contact with the weld pool occurs. However, the rupture of the relatively thick liquid bridge takes place without real problems.

In the high wire feed region the period before necking occurs is extended, which eventually leads to stubbing. This is illustrated for the case of an extremely long short circuit in Fig. 2.9. Kiyohara et al. [2.1] modelled the collapse of current carrying liquid bridges and discriminated between stable and unstable situations. A critical bridge length can be defined in terms of the current density through the electrode and the surface tension of the liquid metal. A stable liquid bridge (bridge length below the critical length) can only become instable when the bridge length is increased due to melting as a result of Joule heating.
Fig. 2.7  Maximum droplet diameter and minimum diameter of the liquid bridge as function of the short circuit time.
Fig. 2.8 Several stages of necking of the liquid bridge during the short circuit period (electrode diameter is 1 mm).
Fig. 2.9 Maximum droplet diameter and minimum diameter of the liquid bridge as function of the short circuit time in the case of high wire feed rate.

2.3.2. Voltage and current

The results of measurements reveal that the short circuit cycle which occurs during short circuiting GMA welding depends on the wire feed rate (average current) and the voltage setting of the power source. This is illustrated in Fig. 2.10 in which the current and voltage are given as function of time for three different values of the wire feed rate at a given voltage setting.

The changes in current and voltage can be described in a more quantitative way by defining characteristic current and voltage values. The current can be characterised by the average arc current, the average short circuit current and the peak current. The voltage values of interest are: the average short circuit voltage, the minimum voltage (immediately after the occurrence of contact between the electrode and the workpiece), the peak voltage (immediately after arc reignition) and the average arc voltage, see Fig. 2.11.

The influence of the wire feed rate on the characteristic values is shown in Fig. 2.12.

The average current of the arc period shows a slight maximum. The increase is the result of the higher wire feed rate, while the decrease during stubbing is due to the failure of arc reignition (I=0). See Fig. 2.12 a.

The minimum voltage (just after the beginning of the short circuit) decreases when stubbing occurs. The average short circuit voltage increases in the case of stubbing as the short circuit time is extended. The peak voltage (the voltage just after reignition) also increases in the stubbing area. The average arc voltage shows a slight maximum under optimal welding conditions. See Fig. 2.12 b.
Fig. 2.10  Voltage (broken line) and current (solid line) as function of time for a) low wire feed rate, b) optimal wire feed rate and c) high wire feed rate.
Fig. 2.11  Current (a) and voltage (b) as function of time and indications of characteristic current and voltage values.
2.3.3. Arc time and short circuit time

The voltage signal was used to determine the arc time and the short circuit time. The short circuit period starts with a sharp voltage drop and ends with an abrupt increase in voltage. At this point the arc period begins.

The arc time and short circuit time as obtained from the experiments are depicted as a function of the wire feed rate in Fig. 2.13 for four values of the voltage. As can be seen in this figure, the curves obtained for the four values of the voltage are similar in shape. With increasing wire feed rate the arc time at first decreases after which it reaches a minimum and increases when the wire feed rate is further increased. The short circuit time decreases slightly in the range of low wire feed rate and increases at larger values of the wire feed rate (when the arc time increases too). With increasing voltage, the minima in both arc time and short circuit time shift to higher values of the wire feed rate.

The tendency of stubbing at high values of the wire feed rate is found for all values of voltage although it manifests itself most noticeably in the low voltage region. Under these conditions the weld pool dimensions are small and the electrode might actually contact the bottom of the weld pool. Furthermore, problems with the reignition of the arc may occur in this region.
Figure 2.14 depicts the results in terms of the arc time ratio ($t_a/\text{cycle}$) and the short circuit time ratio ($t_c/\text{cycle}$) as a function of the wire feed rate. The figure shows that $t_a/\text{cycle}$ decreases, while $t_c/\text{cycle}$ increases when the wire feed rate is increased. Under optimal welding conditions $t_a/\text{cycle}$ and $t_c/\text{cycle}$ are approximately 70 and 30% respectively.

Fig. 2.13 Arc time (O) and short circuit time (●) as function of the wire feed rate for four values of the nominal voltage: a) 15V; b) 16V; c) 18V; d) 20V.
2.3.4. Short circuit frequency

An important feature of the short circuit arc welding process is the short circuit frequency $f_s$. It is the short circuit frequency which is used to tune the welding process under practical conditions, because during the rupture of the liquid bridge and the ignition of the arc sound is emitted.

The value of $f_s$ is equal to the number of short circuits ($n$) per time of measurement ($t_m$) and can easily be obtained with the help of the following equation:

$$ f_s = \frac{n}{t_m} $$

(2.3)

Figure 2.15 shows the influence of the wire feed rate on the short circuit frequency for four values of the nominal voltage. The figure shows that with increasing wire feed rate the short circuit frequency at first increases after which it reaches a maximum and starts to decrease when the wire feed rate is further increased. After the maximum stubbing starts to occur and the welding process becomes irregular.

With increasing voltage, the maximal short circuit frequency decreases, whereas the maximum shifts to higher values of wire feed rate and becomes less pronounced.

The decrease in the maximal value of the short circuit frequency with increasing voltage is directly related to the increase in weld pool width as will be discussed in chapter 6.
Fig. 2.15  Short circuit frequency as function of the wire feed rate for four values of the nominal voltage: a) 15V; b) 16V; c) 18V; d) 20V.
2.3.5. Weld bead appearance and weld pool geometry

In order to evaluate the influence of the welding conditions on the appearance and geometry of the weld, the produced welds were first inspected visually. Specific attention was paid to the regularity of the weld (humping), the occurrence of spatter and the wetting of the weld metal to the workpiece. Figure 2.16 shows a photograph of three welds produced with increasing wire feed rate and constant voltage setting. It can be seen that welding with low wire feed rate results in a small weld bead with a relatively small reinforcement and considerable spatter loss. Increasing the wire feed rate results in a more regular weld bead with smaller spatter loss. A further increase in wire feed rate creates a highly irregular bead with a large wetting angle and high spatter loss.

![Weld bead appearance](image)

**Fig. 2.16** Weld bead appearance for three values of the wire feed rate at constant voltage. a) wire feed rate: 52 mm/s (near open arc), b) wire feed rate: 105 mm/s, c) wire feed rate: 120 mm/s (stubbing); workpiece dimensions 50 x 270 mm.

After the visual inspection the geometric characteristics of the weld (width D, depth of penetration d, reinforcement height h, cross sectional area of the reinforcement A1 and cross sectional area of the penetration A2) were determined from transverse weld cross sections with the help of a Leica CBA 8000 microscope. The weld pool length (l) was determined from the top side of the solidified weld by means of a Neophot microscope. The geometric characteristics of the weld are defined in Fig. 2.17.
With respect to the geometry of the weld the following remarks should be made.

- **Metal loss by spatter from the electrode wire influences the reinforcement.** Under optimal welding conditions the formation of spatter has only a minor influence on the reinforcement, but it starts to play an important role under non-optimal conditions when spatter loss is high.

- **Under non-optimal welding conditions, especially in the case of welding heavy workpieces (three dimensional heat flow), lack of fusion may occur.** Lack of fusion is defined as the lack of contact between weld metal and unmelted workpiece surface.
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- Wetting of the liquid metal is important in relation to the occurrence of lack of fusion [2.23].
- Due to the metal transport the transverse cross section of the weld usually has a fingerlike shape [2.24, 2.25].

The weld bead size and geometry are determined by the heat input and the metal transport. The heat input is governed by the current, the voltage and the travel speed as mentioned in chapter 1.

In Figs. 2.18 and 2.19 the geometric characteristics of the weld are plotted as a function of the wire feed rate. As expected the weld width, the reinforcement height, the reinforcement cross section area and the total cross section area increase with increasing wire feed rate. The decrease of both the penetration depth and the penetration cross section area at high values of the wire feed rate is attributed to the occurrence of stubbing.

In Figs. 2.20 and 2.21 the geometric characteristics of the weld are plotted as a function of the voltage. It can be seen that the weld width, the depth of penetration, the penetration cross section area and the total cross section area increase, whereas the height of reinforcement and the reinforcement cross section area decrease with increasing voltage. The increase of the weld width, the depth of penetration, the penetration cross section area and the total cross section area can be understood when realising that with increasing voltage more heat is transferred to the workpiece per unit time. The decrease of the height of reinforcement and the reinforcement cross section area is due to the fact that the weld width increases, while the melting rate (wire feed rate) remains constant.

The travel speed influences the heat input and thus the dimensions of the weld pool, but has an additional effect on the top view shape of the weld pool, characterised by the length l (see Fig. 2.17). In the case of stationary welding a circular weld pool is formed (not realistic in the case of GMAW). When the travel speed is increased, the weld pool is elongated and obtains an elliptical or a tear drop shape.

Figure 2.22 shows the geometric characteristics of the weld as function of the travel speed with constant wire feed rate and voltage. As the heat input is proportional to the reciprocal of the travel speed, the weld width and reinforcement height decrease when the travel speed is increased. The depth of penetration shows a slight maximum due to a limited heat input for high travel speeds and the occurrence of stubbing when the travel speed is low. The same trends are found for the cross section areas, see Fig. 2.23.

Although the length of the weld pool decreases as function of the travel speed, the ratio of the weld pool length and the weld pool width increases, until stubbing starts to occur, as is shown in Fig. 2.24.
Fig. 2.18  Weld width (□), reinforcement height (●) and penetration depth (○) as function of the wire feed rate, (U=16V).

Fig. 2.19  Total cross section area (□), reinforcement cross section area (●) and penetration cross section area (○) as function of the wire feed rate, (U=16V).

Fig. 2.20  Weld width (□), reinforcement height (●) and penetration depth (○) as function of the average voltage, wire feed rate = 105 mm/s.

Fig. 2.21  Total cross section area (□), reinforcement cross section area (●) and penetration cross section area (○) as function of the average voltage, wire feed rate = 105 mm/s.
Fig. 2.22 Weld width (□), reinforcement height (●) and penetration depth (○) as function of the travel speed, wire feed rate = 105 mm/s, $U=16.7 V$.

Fig. 2.23 Total cross section area (□), reinforcement cross section area (●) and penetration cross section area (○) as function of the travel speed, wire feed rate = 105 mm/s, $U=16.7 V$.

Fig. 2.24 Length/width ratio of the weld pool as function of the travel speed, wire feed rate = 105 mm/s, $U = 16.7 V$. 

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2.3.6. Operating area of short circuiting GMAW

The results presented in the foregoing can be summarised as follows (see Fig. 2.25). At low wire feed rate the arc time is relatively large, i.e. the arc burns a relatively long time before contact is established between the electrode and the weld pool. During this period a relatively large droplet is formed at the end of the electrode. Growth of this droplet continues until the droplet touches the weld pool and a liquid bridge is formed between the electrode and the weld pool. After a relatively short time (short circuit time) the liquid bridge is ruptured under the action of gravity, surface tension and electro-magnetic pinch forces. Upon rupture of the liquid bridge the arc starts again to burn across a relatively long arc gap (arc length) and the cycle is repeated.

With increasing wire feed rate the arc time decreases, which corresponds to an increase in the short circuit frequency. Metal transport and rupture of the liquid bridge still cause no difficulties. This trend continues until stubbing of the electrode in the weld pool starts to occur. Under these conditions the liquid bridge formed at the beginning of the short circuit period is very small and stable and can not be ruptured by the acting forces. Only when the length of the bridge increases, due to Joule heating an unstable situation will occur and the liquid bridge will collapse [2.1].

![Diagram](image)

*Fig. 2.25 Schematic presentation of the general features of short circuiting arc welding.*
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In chapter 6 the influence of weld pool oscillation on the occurrence of stubbing is discussed. It is assumed that stubbing of the electrode in the weld pool is also affected by irregular movement of the surface of the weld pool. Contact occurs at almost zero relative speed, causing the short circuit current to concentrate on an extremely small area. The electromagnetic Lorentz force, associated with the concentrated short circuit current prevents that metal transport takes place [2.26]. Stubbing occurs especially at small arc length (low voltage) and considerably reduces the stability of the welding process.

On the basis of the foregoing one can define an area (operating area) within the voltage-wire feed rate diagram where short circuiting arc welding is possible. This is depicted schematically in Fig. 2.26. When the wire feed rate is low and/or the voltage is high the arc time is long. As a consequence of this droplet growth can take place and droplet detachment will occur, under the action of the gravitational force, before the electrode touches the weld pool. In this situation the metal transport can be classified as free flight transfer. In the opposite situation when the wire feed rate is high and/or the voltage is low stubbing of the electrode in the weld pool takes place, resulting in an irregular process. In between these two situations a region exists where short circuiting arc welding is possible. Of course, short circuiting arc welding is limited at the low heat input side because at too low value of the heat input (low current and low voltage) no weld pool is formed and stubbing of the electrode on the unmelted workpiece occurs.

![Diagram](image)

Fig. 2.26  *Schematic presentation of the short circuit operating area in the voltage-wire feed rate diagram.*

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2.4. Conclusions

On the basis of the description of the process presented in the foregoing, it can be concluded that short circuiting arc welding is a very dynamic process. Current and voltage change in a cyclic way and this cyclic behaviour can be characterised by a number of process parameters, the most important being the arc time, the short circuit time and the short circuit frequency.

Short circuiting arc welding is limited to a specific operating area, because:
- free flight transfer occurs in the high voltage region,
- stubbing takes place in the low voltage/high wire feed rate region,
- no weld pool is formed due to insufficient heat input.

Within the short circuiting arc operating area, welding conditions and performance vary considerably. For instance, arc time and short circuit time change as function of the welding parameters. In the operating area a narrow zone can be assigned where welding conditions are optimal, resulting in good weld bead appearance, low spatter and maximal depth of penetration. The optimal conditions coincide with a minimum in arc time, a maximum in short circuit frequency and the absence of instantaneous short circuits.
References


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Chapter 3

Heat transfer during short circuiting GMA welding

3.1. Introduction

In the previous chapter attention was given to the general features of short circuiting GMA welding. This chapter focuses on heat transfer during short circuiting arc welding. After a description of the theoretical background, including an overview of the various heat sources playing a role, a model is formulated which describes the heat transfer to the electrode wire and to the workpiece.

The validity of this model is tested by means of experiments and calculations and attention is given to the efficiency of the process.

The scope of this chapter is limited to the situation in which the polarity of the electrode wire is positive (DCEP), which is the situation normally encountered in welding practice.

The heat generated during the short circuiting GMA welding process causes melting of the tip of the electrode wire and part of the workpiece, resulting in the formation of the weld pool. The melting electrode acts as filler metal for the weld. The welding conditions determine the wire melting rate and the dimensions of the weld, see section 2.3.5.

The majority of research carried out in the area of GMA welding concerns the free flight (open arc) metal transfer mode. Free flight transfer can be considered as a steady state situation. Pioneering studies in this area were carried out by Lesnewich [3.1] and Wilson et al. [3.2].
As shown in the previous chapters short circuiting arc welding differs from open arc welding [3.3-3.8] in the following ways:

- the arc is not continuously present, but is extinct during the short circuit periods,
- voltage and current fluctuate between arc level and short circuit level, see section 2.2.1,
- variations in the arc length (the electrode extension) are large,
- the position of the solid-liquid interface in the wire varies considerably.

Therefore, modelling of the heat transfer in the case of short circuiting GMAW is more complicated than in the case of open arc welding [3.9-3.11].

During arc welding two major heat sources govern the melting phenomena: arc heating ($Q_a$) and Joule heating of the electrode extension ($Q_h$). Part of the heat generated by the arc enters the electrode wire ($Q_{a-an}$), another part enters the workpiece ($Q_{a-c}$). During welding heat losses occur to the environment due to conduction in the solid wire, conduction in the workpiece, radiation to the environment, conduction and convection of the shielding gas and evaporation of the liquid metal. Finally, heat is lost by the formation of spatter. Figure 3.1 shows the various heat flows schematically. In the following, the major heat sources are briefly discussed.

**Fig. 3.1** Schematic presentation of heat flows during the arc period (left) and the short circuit period (right) in short circuiting arc welding.
3.2. Heat sources

As stated above short circuiting arc welding is normally carried out using direct current with the electrode wire positive (anode) and the workpiece negative (cathode). Under these conditions three heat sources dominate the thermal phenomena during the welding process:

• anodic heating of the electrode wire,
• cathodic heating of the workpiece,
• Joule heating.

3.2.1. Arc heating

Anodic heating of the electrode wire

The arc supplies heat to the anode (electrode wire) by a number of different mechanisms. The heat supplied to the anode by the arc per unit time can be expressed by the following equation:

\[ Q_{a-an} = \left( c_a U_{col} + U_a + \phi_a + \frac{3k(T_{col} - T_a)}{2e} \right) I_a t_a f_s \]  

(3.1)

with:

- \( Q_{a-an} \) = arc heat generated in the anode region per unit time (W)
- \( c_a \) = fraction, value between 0 and 1
- \( U_{col} \) = voltage drop over the arc column (V)
- \( U_a \) = anode voltage drop (V)
- \( \phi_a \) = thermionic work function of the anode (V)
- \( k \) = Boltzmann constant (J/K)
- \( T_{col} \) = temperature of the arc column (K)
- \( T_a \) = temperature of the anode (K)
- \( e \) = electrical charge of an electron (C)
- \( I_a \) = average arc current (A)
- \( t_a \) = average arc time (s)
- \( f_s \) = average short circuit frequency (Hz)

The terms at the right-hand side of the equation represent respectively:

• the fraction of the arc column heat that is transferred to the anode per unit time;
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• the heat generation per unit time in the anode fall region; due to the large voltage gradient the electrons are accelerated towards the anode, where kinetic energy is converted to heat at the point of impact;
• the heat generated per unit time corresponding with the electron absorption in the metal;
• the heat generated per unit time by the electrons due to the difference in electron temperature in the arc column and the temperature of the anode.

Lesnewich [3.1] states that anodic heating is independent of the electrode extension, the arc length and the type of shielding gas (which is contradicted by other investigators [3.7]). The influence of the arc voltage appears to be rather limited, and therefore the term representing the arc column heat which is transferred to the anode is often omitted [3.1, 3.3, 3.4, 3.7]. Under this assumption Lancaster [3.3] estimates the term between brackets in equation (3.1) to be about 5.5 V \((U_a = 1.5 \text{ V}, \phi_c = 3.5 \text{ V}, 3k\Delta T/2e = 0.5 \text{ V})\).

**Cathodic heating of the workpiece**

The arc heat generated at the cathode (workpiece) per unit time can be expressed by:

\[
Q_{a-c} = \left(c_c U_{col} + U_c - \phi_c - \frac{3k(T_{col} - T_c)}{2e}\right) I_a t_a f_s
\]

with:

- \(Q_{a-c}\) = cathodic arc heat per unit time (W)
- \(c_c\) = fraction, value between 0 and 1
- \(U_{col}\) = voltage drop over the arc column (V)
- \(U_c\) = cathode voltage drop (V)
- \(\phi_c\) = thermionic work function of the cathode (V)
- \(k\) = Boltzmann constant (J/K)
- \(T_{col}\) = temperature of the arc column (K)
- \(T_c\) = temperature of the cathode (K)
- \(e\) = electrical charge of an electron (C)
- \(I_a\) = average arc current (A) *)
- \(t_a\) = average arc time (s)
- \(f_s\) = average short circuit frequency (Hz)

*) The current flow in the arc is provided by electrons (emitted by field emission and thermionic emission) and ions. Lesnewich [3.1] divides the total current in fractions \(f_g, f_m\) and \(f_e\), representing the current carried by ionized gas atoms, ionized metal atoms and electrons respectively. Due to the different physical nature of the three zones in the arc, in each of the zones the contribution of the various current carriers is different. The current in the anode fall region is a pure electron flow. In the cathode fall region, however, the ions of the metal contribute significantly to the current flow. This effect is not taken into account in the calculations, which introduces an error of a few percent.
The terms in this equation are similar to the terms in the equation expressing the anode arc heating (equation (3.1)). The main difference is that the emission of electrons and the heat necessary to elevate the temperature of the electrons to the temperature of the arc column will cost rather than supply energy.

Neglecting the influence of the heat from the arc column, Lancaster [3.3] estimates the term between brackets in equation (3.2) to be approximately 11V (U_c ≈ 15 V, \( \Phi_c = 3.5 \text{ V} \), \( 3k\Delta T/2e \approx 0.5 \text{ V} \)).

### 3.2.2. Joule heating

Another major heat source is the heat generated in the electrode extension (stick-out) by Joule heating [3.2, 3.12, 3.13]. Joule heating depends on the electrical resistivity of the electrode material, the current passing through the electrode, the cross section area of the electrode, and the length of the electrode extension. Assuming a uniform current density over the total cross section the Joule heating per unit time can be given by [3.14]:

\[
Q_r = \int_{l=0}^{x} \frac{\rho(l)I^2}{A} dl 
\]

(3.3)

with:

- \( Q_r \) = Joule heat per unit time (W)
- \( x \) = contact-tube-to-workpiece distance (mm)
- \( l \) = distance from the contact tube (mm)
- \( \rho \) = electrical resistivity of the electrode material (Ω⋅mm)
- \( I \) = current (A)
- \( A \) = cross section area of the electrode wire (mm²)

Joule heating becomes especially important in the case of small electrode diameters, long electrode extensions and high electrical resistivity materials, as for instance steel. At this point it should be mentioned that the electrical resistivity is temperature dependent. Generally speaking, the resistivity increases with temperature or heat content. Figure 3.2 depicts the resistivity of mild steel as function of temperature [3.15]. It can be seen that the resistivity increases with temperature and that after the ferrite-austenite transition temperature the gradient is somewhat reduced. This means that, as the temperature increases along the electrode from the contact tube (± 50 °C) towards the arc region, the resistivity increases.
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Joule heating plays a permanent role, during the arc period along the growing electrode extension and during the short circuit period along the entire contact-tube-to-workpiece distance. It should be kept in mind that the length of the current carrying wire may fluctuate in an unpredictable way because the point of electrical contact within the contact tube may easily change in time due to for instance contact tube wear. Also, the location of the arc root relative to the wire tip may vary.

![Diagram](image)

Fig. 3.2 The electrical resistivity of mild steel as function of the temperature [3.15].

Assuming no variation in the temperature in a direction perpendicular to the wire axis, a stationary temperature distribution, a constant wire feed rate and uniform current density over the cross section of the electrode wire, the Joule heating per unit time in the arc period and in the short circuit period can be easily expressed in terms of the electrical process parameters.

During the arc period, as the growing droplet moves towards the weld pool, the electrode extension increases continuously, until contact is established and the electrode extension has become equal to the contact-tube-to-workpiece distance. In this period the current decreases
gradually from the peak current at the moment of reignition of the arc to the arc current level up to the moment when contact is again established. This leads to the following equation for the Joule heating during the arc period:

\[
Q_{r,a} = \frac{\rho_r L_a I_a^2 t_a f_s}{\pi r^2} = U_w I_a t_a f_s
\]  

(3.4)

with:

- \(Q_{r,a}\) = Joule heating per unit time during the arc period (W)
- \(\rho_r\) = electrical resistivity of the electrode material (\(\Omega \text{mm}\))
- \(L_a\) = average electrode extension during the arc period (mm)
- \(I_a\) = average arc current (A)
- \(r\) = electrode wire radius (mm)
- \(t_a\) = average arc time (s)
- \(f_s\) = average short circuit frequency (Hz)
- \(U_w\) = average voltage drop over the electrode extension in the arc period (V)

The voltage drop over the electrode extension during the arc time is assumed to be the minimal voltage at the beginning of the short circuit period [3.9, 3.16].

It is evident that during the short circuit period, Joule heating is the only heating mechanism. As the current rises and necking of the liquid bridge progresses, the current density increases sharply. Since the electrical resistivity is temperature dependent, Joule heating becomes increasingly important, especially during the final stage of the short circuit period. Joule heating during the short circuit period can be expressed by the following equation:

\[
Q_{r,sc} = \frac{\rho_r L_c I_c^2 t_c f_s}{\pi r^2} = U_{sc} I_c t_c f_s
\]  

(3.5)

with:

- \(Q_{r,sc}\) = Joule heating per unit time during the short circuit period (W)
- \(\rho_r\) = electrical resistivity of the electrode material (\(\Omega \text{mm}\))
- \(L_c\) = average electrode extension during the short circuit period (mm)
- \(I_c\) = average short circuit current (A)
- \(r\) = electrode wire radius (mm)
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\[ t_c = \text{average short circuit time (s)} \]
\[ f_s = \text{average short circuit frequency (Hz)} \]
\[ U_{sc} = \text{average voltage drop over the electrode extension in the short circuit period (V)} \]

The voltage drop over the entire contact-tube-to-workpiece distance during the short circuit period is expected to be equal to the average short circuit voltage [3.16].

3.2.3. Other heat sources and heat losses

In addition to the heat sources mentioned in the foregoing, heat can also be generated by other mechanisms, such as the Thomson effect [3.13], by chemical reactions taking place in the arc or in the liquid metal and by the kinetic energy of the droplets [3.17, 3.18]. However, the heat produced by these mechanisms is negligibly small and, therefore, was not taken into account.

Heat losses due to conduction in the solid wire to the contact tube and the torch, thermal radiation from the wire surface and evaporation of the liquid metal were also neglected.

3.3. Model of heat transfer in short circuiting GMA welding

The heat flow equations formulated in the foregoing can be used to model the heat transfer to the electrode (electrode melting rate) and the workpiece. This model is based on the assumption that all heat which is transferred to the electrode wire and the workpiece is used for heating, melting and superheating (heating above the melting point) of the material.

3.3.1. Heat transport to the electrode, the electrode melting rate

During the arc period, heat is supplied to the anode (electrode wire) by arc heating \( (Q_{a-an}) \) and by Joule heating \( (Q_{r,a}) \). During the short circuit period Joule heating \( (Q_{r,sc}) \) is the only heat source. The total amount of heat transferred to the electrode per unit time can thus be expressed by summation of the equations (3.1), (3.4) and (3.5), which yields:

\[ Q_{\text{electrode}} = Q_{a-an} + Q_{r,a} + Q_{r,sc} \]  (3.6)
Under stationary process conditions the melting rate of the electrode wire should be equal to the wire feed rate. When the electrode heat given by equation (3.6) is divided by the heat \( Q_m \), necessary for heating, melting and superheating one gram of electrode material, the electrode melting rate is obtained. The value of \( Q_m \) is given by:

\[
Q_m = \frac{T_m}{T_0} \int c_p(s) dT + \frac{T_a}{T_m} \int c_p(l) dT
\]  \hspace{1cm} (3.7)

with:

- \( T_0 \) = room temperature (K)
- \( T_m \) = melting point of the electrode material (K)
- \( T_a \) = temperature of liquid material at the anode tip (K)
- \( c_p(s) \) = specific heat of the solid material (J/gK)
- \( c_p(l) \) = specific heat of the liquid material (J/gK)
- \( \Delta H_f \) = heat of fusion (J/g)

The equation for the electrode melting rate (EMR) thus becomes:

\[
EMR = \left( U_a + \phi_a + \frac{3k(T_{col} - T_a)}{2e} + c_d U_{col} \right) \cdot I_a I_s + U_w I_a I_w + U_{sc} I_c I_{sc}
\]

\[
\int \frac{T_m}{T_0} c_p(s) dT + \frac{T_a}{T_m} \int c_p(l) dT
\]  \hspace{1cm} (3.8)

3.3.2. Heat transport to the workpiece

During welding the workpiece acts as cathode and receives heat from two heat sources:

- the arc,
- the liquid metal transferred from the electrode to the weld pool.

The Joule heat generated in the workpiece can be neglected, because of the low current density.

Thus, the heat transferred to the workpiece per unit time can be obtained by summation of the equations (3.1), (3.2), (3.4) and (3.5), resulting in the equation:

\[
Q_{workpiece} = (U_a + c_{dU_{col}} + U_c + c_{cU_{col}}) \cdot I_a I_s + U_w I_a I_w + U_{sc} I_c I_{sc}
\]  \hspace{1cm} (3.9)
3.4. Verification of the model

3.4.1. Verification procedure

To evaluate the validity of the heat flow model formulated in the previous section, values of the electrode melting rate (EMR) and of the heat flow to the workpiece \( Q_{\text{workpiece}} \) were calculated with the help of equation (3.8) and (3.9), and compared with values obtained experimentally. With this in mind welding experiments were performed under various experimental conditions. The welding conditions are listed in Table 3.1.

The experimental set-up was similar to that described in the previous chapter. The welding equipment used consisted of a transistorised power source. The workpiece was traversed underneath a fixed water cooled torch and a wire feed unit. Current and voltage were recorded with a sampling frequency of 10 kHz over a period of 400 ms. The obtained data were stored on floppy disk and later analysed by means of a LabVIEW computer program. With this data analysis program average values of arc time \( (t_a) \), short circuit time \( (t_c) \), short circuit frequency \( (f_s) \), short circuit current \( (i_c) \), short circuit voltage \( (U_{sc}) \), voltage drop over the electrode extension \( (U_w) \), short circuit power, arc current \( (I_a) \), arc voltage \( (U_a) \) and arc power were obtained. The physical data used in the calculations are listed in Table 3.2.

The calculated values of the electrode melting rate and of the heat flow to the workpiece were compared with experimental values: the wire feed rate was obtained by means of a Strunk Messmatik wire feed measuring device and \( Q_{\text{workpiece}} \) by means of a calorimetric set-up, which is described in Appendix A.

\[ \text{Table 3.1} \quad \text{Welding conditions used in the verification experiments.} \]

<table>
<thead>
<tr>
<th>workpiece material</th>
<th>mild steel, Fe 360</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrode wire</td>
<td>mild steel (SG2), diam. 1.0 mm</td>
</tr>
<tr>
<td>shielding gas</td>
<td>85% Ar - 15% CO₂</td>
</tr>
<tr>
<td>shielding gas flow rate</td>
<td>16 l/min</td>
</tr>
<tr>
<td>voltage range</td>
<td>14 - 26 V</td>
</tr>
<tr>
<td>current range</td>
<td>50 - 250 A</td>
</tr>
<tr>
<td>wire feed rate range</td>
<td>25 - 300 mm/s</td>
</tr>
<tr>
<td>travel speed</td>
<td>5 mm/s</td>
</tr>
<tr>
<td>slope power source</td>
<td>- 0.5 V/100A</td>
</tr>
<tr>
<td>contact-tube-to-workpiece distance</td>
<td>20 mm</td>
</tr>
</tbody>
</table>
Table 3.2  Physical data used in the calculations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_a$ (anode voltage drop)</td>
<td>3 V</td>
<td>-</td>
</tr>
<tr>
<td>$U_c$ (cathode voltage drop)</td>
<td>13 V</td>
<td>-</td>
</tr>
<tr>
<td>$c_a$ (anode column fraction)</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>$c_c$ (cathode column fraction)</td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td>$\phi_a, \phi_c$ (workfunction)</td>
<td>3.5 V</td>
<td>[3.3]</td>
</tr>
<tr>
<td>$\int c_p(s)dT + \Delta H_f$</td>
<td>1311 J/g</td>
<td>[3.17,3.19]</td>
</tr>
<tr>
<td>$c_p(l)$ (specific heat of liquid metal)</td>
<td>0.6694 J/gK</td>
<td>[3.15]</td>
</tr>
<tr>
<td>$T_{col}$ (column temperature)</td>
<td>10000 °C</td>
<td>[3.3]</td>
</tr>
</tbody>
</table>

*) In literature data on the energy required to raise the temperature of steel from room temperature to the melting point (including phase transformations and melting) show considerable variations [3.3, 3.17, 3.19-3.21]. In this study the value given by Essers et al. [3.17] is used.

With respect to the energy necessary to superheat the liquid metal (the third term at the right-hand side of equation (3.7)), it should be noted that the temperature of the anode tip ($T_a$) depends on the welding conditions. Pokhodnya et al. [3.22] state that the temperature of the anode tip increases with welding current and voltage. Meyendorf et al. [3.18] measured the anode tip temperature during short circuiting arc welding and found that this temperature increases linearly with the duration of the arc period, see Fig. 3.3. However, the anode tip temperature is limited by the occurrence of open arc welding. In view of this, the data of Meyendorf et al. [3.18] were used for arc periods below 20 ms, whereas for arc periods longer than 20 ms, the droplet temperature measured by Jelmorini et al. [3.23] was used.

![Fig. 3.3 Anode tip temperature as function of the duration of the arc period](image)

Fig. 3.3  Anode tip temperature as function of the duration of the arc period; $\bullet I=140A, U=18V$; $\circ I=200A, U=22V$ [3.18]. The dashed line represents the droplet temperature in the case of open arc welding [3.23].
3.4.2. Heat transport to the electrode (electrode melting rate)

In Fig. 3.4 the electrode melting rate calculated with equation (3.8) is plotted as function of the measured wire feed rate. It can be seen that both quantities are about equal in the lower range, but start to differ when stubbing conditions are approached. When stubbing of the wire in the weld pool occurs, melting as a result of Joule heating during the short circuit period becomes more and more important, whereas both the contribution of anodic arc heating and Joule heating during the arc period decrease. The observed deviation from the straight line when stubbing conditions are approached is due to the fact that under these conditions less heat is used than calculated, as small parts of the electrode wire remain unmelted. Experiments were also performed with constant wire feed rate and variable voltage. The results of these experiments are presented in Fig. 3.5. Again, good agreement between calculated and measured data is found. Furthermore, it appears that the contributions due to anodic arc heating as well as Joule heating are virtually independent of the voltage, which is consistent with expectation (see equation (3.8)). However, under stubbing conditions, the calculated electrode melting rate start to deviate from the measured wire feed rate because of failure of arc reignition, which results in incomplete melting of the electrode wire.

![Graph showing relationship between melting rate and wire feed rate](image)

**Fig. 3.4** Calculated electrode melting rate as function of the measured wire feed rate.
In Fig. 3.6 the Joule heating - anodic arc heating ratio \( (Q_r/Q_{a-an}) \) is plotted as a function of wire feed rate. The term \( Q_r \) represents the total Joule heating and includes both the Joule heating generated during the arc period and that generated during the short circuit period. The figure shows that the contribution of Joule heating increases with increasing wire feed rate and becomes about 50% of the contribution of the anodic arc heating under normal welding conditions.

Saraev et al. [3.24] found that in the case of open arc welding the amount of heat generated in the electrode extension may reach about 16% of the entire arc heat, which is about 55% of the heat required for melting of the electrode. The electrode extension length, however, is very important, and may change this value dramatically [3.1, 3.2, 3.12].

As expected, when stubbing starts to occur, the influence of Joule becomes dominant.
3.4.3. Heat transport to the workpiece

In Fig. 3.7 the heat flow to the workpiece, calculated with the help of equation (3.9), is plotted as a function of the measured wire feed rate. Also plotted in this figure are heat flow values obtained experimentally by means of a calorimeter [3.25], see appendix A. The figure shows that there is good agreement between the calculated and the measured values, which confirms the validity of the heat flow model.

It appears that the heat flow to the workpiece increases with increasing wire feed rate, until stubbing occurs. The observed increase in heat flow is of course due to the increase of the average current. The difference between measured and calculated data is ascribed to heat losses in the calorimeter.

Figure 3.8 shows the calculated and measured heat flow to the workpiece as function of the voltage. Again, good agreement appears to exist between the calculated and the measured values. It can be seen that both the calculated and the measured heat flow increase slightly with voltage. This increase is apparently due to the increasing contribution of heat flow from the arc column (see equation (3.8)).

![Graph showing heat flow to the workpiece as function of the wire feed rate.](image)

*Fig. 3.7*  Heat flow to the workpiece as function of the wire feed rate, measured by means of a calorimeter (O) and calculated (●).
3.5. Heat transfer efficiency

An important feature of the arc welding process is the effectiveness of the heat transfer. This effectiveness can be expressed in a number of ways [3.21]. In this study it is expressed in terms of process efficiency and melting efficiency.

3.5.1. Process efficiency

The process efficiency is defined as the ratio of the heat entering the workpiece per unit time ($Q_{\text{workpiece}}$) and the total energy supplied during welding per unit time ($UI$) [3.5, 3.21, 3.26-3.27]:

$$\eta_p = \frac{Q_{\text{workpiece}}}{UI} \cdot 100\%$$  \hspace{1cm} (3.10)
Using equation (3.10) values of $\eta_p$ were obtained for different welding conditions. Figure 3.9 shows the process efficiency as function of the wire feed rate. As can be seen the process efficiency decreases slightly with wire feed rate. This decrease can be ascribed to an increase in radiation loss due to the increase in arc current (hotter arc).

The process efficiency is plotted as function of the voltage in Fig. 3.10. Also in this case a decreasing tendency can be observed. This effect can be explained by an increase in radiation loss from the arc column due to the increase in arc length (longer arc).

**Fig. 3.9**  Calculated process efficiency as function of the wire feed rate.

**Fig. 3.10**  Calculated process efficiency as function of the voltage.
As shown in Figs. 3.9 and 3.10 the process efficiency in the case of short circuiting GMA welding lies in the range of 80 to 95%. This is considerably higher than the process efficiency in the case of open arc GMA welding, which is about 70% [3.5]. The difference in process efficiency between short circuiting arc welding and open arc welding is presumably due to the reduced influence of the radiation from the arc.

3.5.2. Melting efficiency

The effectiveness of the heat transport to the workpiece can also be described by means of the melting efficiency. The melting efficiency represents the fraction of the total supplied energy that is actually used for heating and melting of the metal (i.e. for the actual formation of the weld pool). This can be expressed by the following equation:

$$\eta_m = \frac{A \nu_t \rho_s}{UI} \left( \frac{T_m}{T_0} \int c_p(s)dT + \Delta H_f \right) \cdot 100\% \quad (3.11)$$

with $A$ the transverse cross section area of the weld, $\nu_t$ the travel speed and the other quantities as defined in the foregoing. Values for the melting efficiency lie in the range of 35 to 50%, which is considerably higher than the values obtained in the case of open arc welding [3.28].

It should be noted that the energy necessary for heating the liquid metal above the melting point is not included in equation (3.11).

The melting efficiency can be split into the electrode melting efficiency and the workpiece melting efficiency.

The electrode melting efficiency is given by:

$$\eta_{m-e} = \frac{A_1 \nu_t \rho_s}{UI} \left( \frac{T_m}{T_0} \int c_p(s)dT + \Delta H_f \right) \cdot 100\% \quad (3.12)$$

with $A_1$ the cross section area of the reinforcement.

The workpiece melting efficiency can be represented by the equation:
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\[
\eta_{m-w} = \frac{A_2 v_f \rho S \left( \frac{T_m}{T_0} \int_c \rho_f(s) dT + \Delta H_f \right)}{U L} \times 100\%
\]  

(3.13)

with \(A_2\) the penetration cross section area.

Using the data presented in section 2.3.5 the melting efficiency was determined by means of equations (3.11), (3.12) and (3.13). The transverse cross section areas of the welds were measured using optical microscopy (Leica CBA 8000). The results are shown in Fig. 3.11. In this figure the melting efficiency is depicted as function of the wire feed rate at constant voltage. It can be seen that the melting efficiency increases with increasing wire feed rate until stubbing occurs. This is in agreement with expectation, since with increasing heat input, accompanying the increase in wire feed rate, the heat which enters the workpiece is used more effectively for melting [3.21].

![Graph showing melting efficiency as a function of wire feed rate.](image)

**Fig. 3.11** Total melting efficiency (■), electrode melting efficiency (○) and workpiece melting efficiency (●) as function of the wire feed rate at constant voltage.

Figure 3.12 shows the melting efficiency as function of the voltage at constant wire feed rate. It can be seen that the melting efficiency decreases with voltage, which can be understood by realising that with increasing voltage the average arc length increases and consequently a larger part of the heat produced is lost by radiation.
3.6. Conclusions

On the basis of the results presented in this chapter the following conclusions can be drawn.

- Heat flow during short circuiting gas metal arc welding is governed by anodic arc heating of the electrode, cathodic arc heating of the workpiece and Joule heating of the electrode.
- A model is derived which predicts the heat transfer to the electrode and to the workpiece during the welding process.
- Values of the electrode melting rate and of the heat flow to the workpiece predicted by the model are consistent with experimentally obtained data.
- The process efficiency of the short circuiting GMA welding process lies between 80 and 95%, depending on the welding conditions.
- The melting efficiency in the case of short circuiting GMA welding is 35 to 50%, depending on the welding conditions.

![Graph showing melting efficiency vs voltage](image_url)

*Fig. 3.12* Total melting efficiency (■), electrode melting efficiency (○) and workpiece melting efficiency (●) as function of the voltage at constant wire feed rate.
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Chapter 4

Metal transport during short circuiting GMA welding

4.1. Introduction

This chapter focuses on the characteristic features of the metal transport taking place during the short circuiting arc welding process. In chapter 2 an outline is given of the general principles of metal transport during short circuiting arc welding. It was shown that short circuiting GMA welding is characterised by regular contact between the pendant droplet at the end of the continuously fed electrode wire and the weld pool. In this contact period metal transport takes place from the electrode wire to the weld pool. The main forces that govern metal transport are: the gravitational force, the electro-magnetic Lorentz force and the surface tension. During the short circuit period the Lorentz force becomes gradually more important and eventually controls the rupture of the liquid bridge between the electrode wire and the weld pool.

In the case of short circuiting GMA welding, mass transfer occurs by pinching of the liquid metal bridge during the short circuit period. The general features of this process are described in section 4.2.

An erroneous and unwanted way of mass transfer is spatter formation. This phenomenon depends on the welding conditions and can give rise to various problems. Relevant information about spatter formation can be obtained by weighing techniques and by means of high-speed filming. Successively, attention is given to the generation of spatter (section 4.3), the origin of spatter (section 4.4), the influence of the power source (section 4.5) and the influence of the current induced magnetic field (section 4.6).
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4.2. Regular mass transfer

As stated above, mass transfer in short circuiting GMA welding takes place during the short circuit period by pinching of the liquid bridge between the electrode wire and the workpiece under the action of the Lorentz force. An important measure of this mass transfer is the average mass \( m_s \) of the liquid metal transferred during one short circuit cycle. It must be expected that the value of \( m_s \) depends on the welding parameters, in particular the wire feed rate. Wegrzyn et al. [4.1] investigated droplets produced during short circuiting GMAW, and found that the welding parameters considerably influence the droplet dimensions.

In order to obtain quantitative information about the metal transfer during short circuiting GMA welding, experiments were carried out under various welding conditions using the experimental set-up and materials described in chapter 2. The value of \( m_s \) was calculated from the wire feed rate \( v \), the radius of the electrode wire \( r \) and the average short circuit frequency \( f_s \) with the help of the equation:

\[
m_s = \frac{\rho \pi r^2 v}{f_s}
\]

(4.1)

with \( \rho = 7.8 \times 10^3 \text{ kg/m}^3 \), the density of mild steel at room temperature.

The influence of the wire feed rate on the average transferred mass of liquid metal per short circuit is shown in Fig. 4.1 for four different values of the voltage. It appears that despite the increasing wire feed rate, the average mass of the transferred liquid metal per short circuit at first decreases as a result of the increasing short circuit frequency, see Fig. 2.15. After this initial decrease the transferred mass reaches a minimum and starts to increase when the wire feed rate is further increased (stabbing). As can be seen in Fig. 4.1, the minimal value of \( m_s \) increases, whereas the minimum shifts to higher values of wire feed rate when the voltage is increased.

As mentioned above under certain conditions stabbing of the electrode wire occurs. These conditions reflect the situation where the liquid bridge is so short that rupture is not possible any more. Kiyohara et al. [4.2] considered the situation from a theoretical point of view and calculated this critical length of the liquid bridge. They found values which are of the same order of magnitude as those found in the present work.
Fig. 4.1 The mass transferred per short circuit as function of the wire feed rate for four values of the nominal voltage: a) 15V; b) 16V; c) 18V; d) 20V.
4.3. Spatter generation

One of the main problems of GMA welding is the occurrence of spatter [4.3]. Spatter can be defined as metal droplets which leave the electrode but do not enter the weld pool and/or droplets which leave the weld pool under the action of explosive forces. The formation of spatter has a number of negative consequences. It may lead to poor weld quality, such as lack of fusion due to adhesion of spatter on the weld groove and porosity due to turbulent gas flow, as spatter easily sticks to the inside of the nozzle. Furthermore, spatter results in a reduced productivity, as in most cases it has to be removed from the workpiece after welding. Spatter can also have a negative influence on corrosion resistance (especially in the case of stainless steel) and the adhesion of paint.

The welding parameters / process conditions which influence the spatter behaviour during welding can be divided into three categories:
• the electrical parameters [4.4-4.8],
• the chemical composition of the shielding gas [4.9, 4.10],
• the chemical composition of the electrode wire [4.11, 4.12].

Hasagawa [4.13] and Potapevski [4.14] distinguish various types of spatter and their origin during GMA welding in general. In the case of short circuiting welding only a limited number of these types of spatter can be observed.

High-speed filming reveals that in the metal transport process during short circuiting GMA welding two decisive moments occur, as illustrated in Fig. 4.2. The first one is the moment of contact between the droplet and the weld pool. Normally, this initial contact will immediately lead to the formation of a liquid bridge by rapid extension of the contact area. However, under specific circumstances the droplet is rejected from the weld pool after a very short contact period. This phenomenon is called an instantaneous short circuit [4.15]. Instead of being pulled into the weld pool, the droplet is pushed upwards and thus has the opportunity to grow to an excessive size. It is believed that the electro-magnetic pinch force and the surface tension force are responsible for this rejection. Instantaneous short circuiting results in a disturbance of the metal transport and in irregular process behaviour, accompanied by spatter.
The second important moment in the metal transport process is the rupture of the liquid bridge between the solid electrode and the weld pool. The violence of the rupture influences the amount of spatter [4.16, 4.17]. As the inward directed Lorentz force, which pinches the liquid metal, is proportional to the square of the current, the magnitude of the short circuit current is crucial.

In literature a large number of papers and patents can be found dealing with methods and techniques aimed at reducing the spatter loss. The majority of these methods and techniques focusses on modifying the current and voltage output of the power source at these specific critical moments, see for instance Fig. 4.3. In particular, the reduction of the current at the end of the short circuit period is of importance, because this limits the pinch force and therefore avoids a violent rupture of the liquid metal bridge [4.18-4.20].

Another approach is to limit the droplet growth, by decreasing the current, after a pre-set arc time. This method intervenes the process only in the case of excessive droplet growth. An additional advantage is a reduced electro-magnetic force at the moment of first contact between droplet and weld pool, which suppresses the counteracting pinch force. Figure 4.4 shows schematically the current as function of time for the situation that the current signal is not modified and the case that current modification takes place. Welding with this device results in a more regular short circuiting process [4.21].
Fig. 4.3 Illustration of the modification of the current and voltage signal [4.18].

Fig. 4.4 Schematic presentation of the current as function of time: a) non-modified current signal; b) modified current signal.
To obtain detailed information about spatter formation in the case of short circuiting GMA welding, experiments were carried out under various welding conditions. For each set of conditions the amount of spatter loss was determined with the help of a weighing technique using the following procedure.

Before welding, the weight of the workpiece was determined \((m_1)\) with a balance (Mettler). After welding and removing the spatter from the workpiece, the workpiece was weighed again \((m_2)\). Furthermore, the consumed wire length was measured and converted into the weight of the supplied wire \((m_3)\).

The spatter loss \((SL)\) was calculated from the values of \(m_1\), \(m_2\) and \(m_3\) with the following equation:

\[
SL = \left(\frac{m_1 + m_3 - m_2}{m_3}\right) \times 100\%
\]

(4.2)

Figure 4.5 gives the spatter loss as a function of the wire feed rate for three values of the voltage. Generally speaking, the spatter loss decreases with increasing wire feed rate until stubbing starts to occur, which is accompanied by excessive spatter.

The decrease in spatter loss with increasing wire feed rate is directly related to the fact that with increasing wire feed rate the size of the droplet at the moment of contact (and, hence, the size of the liquid bridge) becomes smaller, which reduces the possibility of droplet rejection and / or explosive rupture of the liquid bridge. When the size of the liquid bridge becomes too small, pinching of the liquid bridge is not possible any more and stubbing is the result.

As expected the minimum in spatter loss corresponds with a minimum in transferred mass per short circuit (see Fig. 4.1) and with a maximum in short circuiting frequency (see Fig. 2.15). As can be seen in Fig. 4.5 the minimum in spatter loss shifts toward higher values of the wire feed rate with increasing voltage.
Fig. 4.5  Spatter loss as function of the wire feed rate for three values of the nominal voltage: a) $U=15V$; b) $U=16V$; c) $U=18V$. 
4.4. Origin of spatter

Analysis of high-speed films taken with a Hicam K20S4W high-speed film camera during short circuiting GMA welding under optimal conditions reveals that the origin of spatter is the liquid bridge. In fact it appears that spatter formation is due to the explosive rupture of the liquid bridge.

To confirm this observation, additional experiments were carried out with an electrode wire and a workpiece having different chemical composition. When welding with this wire/workpiece combination, the chemical composition of the collected spatter gives information about where the spatter originates.

For the welding experiments a mild steel electrode wire of the type SG2 was chosen, while the workpiece was a stainless steel plate of the type AISI 316. The chemical composition of the electrode wire and the workpiece are given in Table 4.1. As can be seen in this table the electrode wire and workpiece differ particularly in chromium and nickel contents. After welding the spatter was collected and the chromium and nickel contents of the collected spatter was analysed by Atomic Absorption Spectroscopy (AAS-flame), Perkin Elmer 1100. Table 4.2 gives the chromium and the nickel contents of the spatter for different values of the wire feed rate and a fixed value of the voltage (16V).

The table shows that the chromium and the nickel contents of the spatter match those of the electrode wire much better than those of the workpiece. This confirms the finding that spatter originates at the liquid bridge. For comparison Table 4.3 gives the chromium and nickel contents of the weld metal for different values of the wire feed rate at a voltage of 16V.

Table 4.1  Chemical composition of electrode wire (SG2) and workpiece (AISI316) in wt%.

<table>
<thead>
<tr>
<th>element</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>Mo</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrode</td>
<td>1.44</td>
<td>1.25</td>
<td>0.022</td>
<td>0.017</td>
<td>0.11</td>
<td>&lt;0.013</td>
<td>0.069</td>
</tr>
<tr>
<td>workpiece</td>
<td>1.33</td>
<td>0.46</td>
<td>16.80</td>
<td>10.53</td>
<td>0.16</td>
<td>2.07</td>
<td>0.038</td>
</tr>
</tbody>
</table>

Table 4.2  Chromium and nickel contents of the collected spatter in wt% for different values of the wire feed rate v (mm/s).

<table>
<thead>
<tr>
<th>v</th>
<th>66</th>
<th>86</th>
<th>103</th>
<th>117 (stubbing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromium</td>
<td>0.87</td>
<td>0.85</td>
<td>0.50</td>
<td>0.020</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.56</td>
<td>0.65</td>
<td>0.42</td>
<td>0.031</td>
</tr>
</tbody>
</table>
Table 4.3 Chromium and nickel contents of weld metal in wt% for different values of the wire feed rate \( v \) (mm/s).

<table>
<thead>
<tr>
<th>( v )</th>
<th>66</th>
<th>86</th>
<th>103</th>
<th>117 (stubbing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromium</td>
<td>5.76</td>
<td>5.11</td>
<td>5.72</td>
<td>0.80</td>
</tr>
<tr>
<td>Nickel</td>
<td>3.26</td>
<td>3.12</td>
<td>1.41</td>
<td>0.51</td>
</tr>
</tbody>
</table>

**4.5. Influence of power source**

As stated above, spatter is caused by explosive rupture of the liquid bridge between the electrode and the weld pool under the action of the electro-magnetic Lorentz force. Since the Lorentz force is proportional to the square of the current, it is evident that the power source and in particular the voltage - current characteristic of the power source, plays an important role in spatter formation. For short circuiting GMA welding in most cases a power source with (near) horizontal voltage - current characteristic is used. This implies that the short circuit current can rise to high values. However, care should be taken that the current does not rise too rapidly, since a rapid rise of current results in a rapid rise of the pinch force, which would increase the possibility of explosive rupture of the liquid bridge. Thus knowledge and control of \( \text{d}I/\text{d}t \) is necessary to minimise spatter formation and to provide stable process behaviour [4.7, 4.22, 4.23]. In line with this, attempts have been made to modify power sources as was already shown in section 4.3.

**4.6. Influence of current induced magnetic field**

In the previous sections the influence of the current on the electro-magnetic Lorentz force and, hence, on spatter formation was briefly discussed. Another important factor that influences the magnitude and direction of the electro-magnetic force is the current induced magnetic field. It can be shown that an asymmetric magnetic field density around the liquid bridge, causes the Lorentz force to push the bridge in forward or backward direction, depending on the current direction in the workpiece, see Fig. 4.6. The phenomenon is similar to magnetic arc blow [4.24]. In view of the foregoing it must be expected that the torch position and in particular the torch travel angle (the angle between the electrode axis and the direction of travel) influences the
Lorentz force and thus the spatter formation. In order to explore this influence, a number of experiments with different torch travel angles was carried out (between a $10^\circ$ drag angle and a $10^\circ$ push angle). In each situation the spatter loss was measured.

The results of the measurements are presented in Fig. 4.7 and show that a minimum in spatter loss occurs at a slightly dragging torch position. In this position the electrode is perpendicular to the surface of the weld pool. The figure also shows that welding with a pushing torch angle results in higher spatter loss than with a dragging torch angle. This is due to the increased asymmetry of the magnetic field around the electrode under pushing conditions.

![Diagram](image)

**Fig. 4.6**  Asymmetric magnetic field density around liquid bridge.

![Graph](image)

**Fig. 4.7**  The influence of the torch travel angle on spatter loss.
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4.7. Conclusions

The results presented in this chapter lead to the following conclusions.

- Metal is transferred from the electrode wire to the workpiece during the short circuit period under the action of the surface tension and the Lorentz force. The mass of liquid metal transferred during one short circuit cycle reaches a minimum for specific combinations of wire feed rate and voltage.

- An unwanted phenomenon during short circuiting GMA welding is the generation of spatter. Spatter originates mainly from the liquid bridge between the electrode wire and the workpiece and is released as the bridge is ruptured. Spatter loss shows a minimum under the same conditions for which the transferred mass per short circuit is minimum. Spatter loss depends on the voltage-current characteristic of the power source used and on the torch angle and increases dramatically when stubbing occurs.
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Chapter 5

Stability of the short circuiting GMA welding process

5.1. Introduction

This chapter deals with the stability of the short circuiting GMA welding process. Process stability is an extremely important feature, which is decisive for the application possibilities of the process.

The process stability can be quantified in a number of ways. Ondrejcek [5.1] used the statistical evaluation of the short circuit frequency to determine the boundaries between the various metal transfer modes in GMA welding. He found that with increasing arc time, conditions are created for changes in the mode of metal transfer from short circuit transfer to drop transfer. Under these conditions the scatter in short circuit frequency increases significantly.

Liu et al. [5.2] carried out an investigation of the statistical variation in the time between successive droplet transfers and measured the droplet transfer rate as a function of current and voltage. The welding parameters with the smallest variation in time between successive droplets were found to correspond with the shortest transfer period, the least spatter and the smoothest weld bead surface.

Lucas [5.3] studied the effects of process parameters on the stability of short circuiting arc welding using the standard deviation in peak current value (the maximum welding current during the short circuit period) as an indicator of the stability and regularity of the process.
Peak current is related to the short circuit time and the inductance of the electrical circuit. During the short circuit period the current rises exponentially with time. In the case of a constant inductance in the welding circuit, a high peak current value is associated with an extended short circuit period. Accordingly, the standard deviation in peak current gives information about the regularity of the rupture of the liquid bridge between the electrode wire and the weld pool.

Gupta et al. [5.4] determined the probability density distribution of current, voltage, short circuit time and arc time for several welding conditions. They found that spatter loss depends on the stability of the welding process which in turn is influenced by the frequency of the short circuits, the duration of the short circuits, the arc period, and the voltage-time and current-time fluctuations. Similar experiments were carried out by Dilthey et al. [5.5]. These authors found that the frequency distribution of the time between two short circuits did not show the expected similarity to a single peak Gaussian distribution. Instead several peaks were observed. As possible explanation for this phenomenon the occurrence of weld pool oscillation was suggested. Rehfeldt et al. [5.6] also found a double peak in the arc time distribution in the case of overlap welding. They concluded that even if the droplet does not contact the weld pool during the first oscillation, the resulting longer arc time is not irregular but has a Gaussian distribution.

Recently, increasing attention is being paid to the phenomenon of spatter formation which can occur during GMA welding and is highly undesirable as it results in poor weld bead quality, porosity due to incomplete gas shielding and reduction of the efficiency of the welding process, see chapter 4.

Ando and Hasagawa [5.7] mention four major causes for spatter formation: eruption of gas bubbles in the weld pool, explosive gas generation in the droplets, operation of electromagnetic forces in the arc and reignition of the arc after a short circuit. Zaruba [5.8] claims that spatter originates from the shock waves caused by the rupture of the liquid bridge. Gupta et al. [5.9, 5.10] investigated the influence of a number of parameters during welding with carbon dioxide as shielding gas. Spatter losses in the range of 3 to 15% were reported.

In chapter 4 the results of spatter loss measurements are presented. It was found that optimal welding conditions result in a minimum spatter loss. This is in agreement with the results obtained by Gupta et al. [5.4] and Lancaster [5.11], who found that a minimum amount of spatter is generated during stable operation of the welding process, i.e. when current and voltage fluctuations are regular in time.
The foregoing suggests that the evaluation of the stability of the short circuiting GMA welding process in terms of just one parameter is inadequate. A better approach is to relate the stability to a combination of parameters.

In line with this, Shinoda et al. [5.12] consider the combined effect of current and voltage on the stability of the process by means of a current-voltage diagram. Several types of irregularities, such as instantaneous short circuits and abnormal spikes of the voltage during reignition of the arc, can be detected in this way. In order to quantify the stability of the process, an algorithm is proposed which determines the area of the current-voltage signal loop. The standard deviation in loop area is an indication of the stability of the welding process. As an illustration Fig. 5.1 gives the current - voltage loops for the case of welding under stable welding conditions and for the case of stubbing.

![Diagram](image)

**Fig. 5.1**  Current - voltage loops: a) stable process conditions; b) unstable process conditions (stubbing).
In this chapter different aspects of the stability of the short circuiting GMA welding process will be discussed.

First, the experimental data obtained during the welding experiments described in the previous chapters are further analysed. From the collected current and voltage data, average values, distribution spectra and standard deviations were calculated. From these quantities criteria for process stability were selected, resulting in a line (locus) of maximum stability in the voltage - wire feed rate diagram.

At this point it must be noted that it is also possible to express the process stability in terms of spatter loss, because the occurrence of spatter is commonly associated with irregularities of the process. However, spatter loss is measured after welding. As an indicator of the process stability in a feedback system, spatter loss is therefore inadequate.

5.2. Distribution of process parameters

5.2.1. Voltage distribution

In chapter 2 mention was made of the fluctuation of the voltage between arc level and short circuit level. To quantify this fluctuation cumulative counts of the voltage over a period of 400 ms (sample frequency 10 kHz) were made for several values of wire feed rate at constant voltage setting (U=16V). The results are depicted in Fig. 5.2.

The different distributions presented in Fig. 5.2 all show a similar pattern. The lower end of the distribution starting at approximately 1 V represents the voltage just after the start of the short circuit. During the short circuit period the voltage over the liquid bridge steadily increases due to necking of the liquid bridge and increase of the (temperature dependent) electrical resistivity of the liquid metal. At a voltage of approximately 8V, the liquid bridge is ruptured and the arc is reignited. At the moment of arc reignition, the voltage jumps to a maximum. The high voltage range in the voltage distribution is associated with that specific moment of the short circuit cycle. The voltage peak immediately after the rupture of the liquid bridge can be extremely high, depending on the power source used and the parameter setting selected. Rehfeldt et al. [5.13] even measured voltage peaks of approximately 200 V within 60 ns after the rupture of the short circuit. When the arc is re-established, the voltage gradually decreases towards the average arc voltage level. The peak in the voltage distribution corresponds with this average arc voltage level, as the arc period covers the major part of the short circuit cycle.
Fig. 5.2  The distribution of voltage for different wire feed rates at constant voltage setting (U=16V):
   a) 52 mm/s; b) 68 mm/s; c) 85 mm/s; d) 93 mm/s; e) 102 mm/s; f) 106 mm/s; g) 120 mm/s.
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The influence of the wire feed rate on the voltage distribution can be explained as follows. A low wire feed rate is accompanied by relatively long periods of intermediate/high voltage (arc voltage) and relatively short periods of low voltage (short circuit voltage), because the short circuit frequency is low. This is reflected by a sharp peak in the voltage range near the average arc voltage and a low level region at low voltage.

Increasing the wire feed rate results in an increased short circuit frequency. Consequently, the contributions of the short circuit period and the arc reignition increase. This trend is continued when wire feed rate is further increased up to the moment that stubbing starts to occur. In the case of stubbing, the distribution of the short circuit voltage range is extended to about 14 V and a small peak appears at this voltage which corresponds with rupture of the liquid bridge followed by reignition of the arc, whereas the peak coupled to the reignition of the arc decreases, see Fig. 5.2 g.

5.2.2. Current distribution

The cycle of events taking place during short circuiting arc welding can also be characterised by fluctuations in the welding current, as is mentioned in chapter 2. In the time weighed current distribution again the various stages of the short circuit cycle can be distinguished. Figure 5.3 show the current distribution over a period of 400 ms (sample frequency 10 kHz) for several values of the wire feed rate at constant voltage setting (U=16V). The slope of the power source and the inductance of the electrical circuit is maintained at a constant level for all experiments. For low values of wire feed rate, Fig. 5.3 a, a sharp peak is present in the distribution due to the long duration of the arc period. As short circuits are encountered only occasionally, the number of counts in the high current range is limited. When the wire feed rate is increased the sharp arc current peak decreases while the intensity of the short circuit current range increases, Fig. 5.3 b to f. The distribution shows a small and broad maximum around the peak current as the maximum current level is sometimes prolonged before rupture of the short circuit occurs. A further increase in wire feed rate results in stubbing, Fig. 5.3 g. In the case of stubbing the maximum current during the short circuit increases and, hence, the current distribution extends towards higher current levels. This is due to the fact that rupture of the liquid bridge becomes increasingly difficult. A second feature of stubbing is the appearance of a low level current peak, associated with failure of arc reignition.
Fig. 5.3 Distribution of current for different wire feed rates at constant voltage setting (U=16V):

a) 52 mm/s; b) 68 mm/s; c) 85 mm/s; d) 93 mm/s; e) 102 mm/s; f) 106 mm/s; g) 120 mm/s.
5.2.3. Distribution of short circuit time, arc time and short circuit frequency

In addition to the distributions of the voltage and the current, it is also interesting to consider the distribution of the short circuit time and the arc time. The latter distributions can be easily obtained from the collected data of current and voltage (see chapter 2).

Figure 5.4 shows the distribution of the short circuit time for different values of the wire feed rate at a voltage of 16V. For low values of the wire feed rate, Fig. 5.4 a and b, the distribution shows a sharp single peak near 2.5 ms. When increasing the wire feed rate this peak broadens somewhat but is maintained until the stubbing region is reached. In the case of stubbing, Fig. 5.4 g, the distribution becomes relatively flat, due to the large variation in short circuit time. Not only instantaneous short circuits (contact between droplet and weld pool without metal transfer, as the first contact between droplet and weld pool is immediately interrupted by the electro-magnetic pinch force and surface tension), but also long short circuits are encountered. Under these conditions appropriate arc reignition fails and droplet growth is disturbed. During the subsequent short circuit, melting of the 'solid bridge' must occur before rupture of the bridge can take place, which results in an extended short circuit time.

The distribution of the arc time under the same experimental conditions is shown in Fig. 5.5. For low wire feed rate, a peak can be observed at relatively high arc time, indicating a prolonged droplet growth period. Increasing the wire feed rate leads to reduction of the arc time and the peak shifts towards lower values of the arc time. A further increase in wire feed rate (stubbing conditions) leads to a flattened arc time distribution, Fig. 5.5 g.

The distribution features of the short circuit time and the arc time are combined in the distribution of the short circuit frequency. The frequency distribution for different values of the wire feed rate is depicted in Fig. 5.6. For low wire feed rate, a low frequency peak is observed. With increasing wire feed rate, the amplitude of the low frequency peak decreases and broadens, whereas also a second peak appears at higher frequency. This second high frequency peak becomes gradually more important and finally dominates the first one. Stubbing (Fig. 5.6 g) detoritates the regularity of the process and a wide distribution of the short circuit frequency is observed.

The presence of peaks in the frequency distribution is attributed to the occurrence of weld pool oscillations. This will be further discussed in chapter 6.
**Fig. 5.4** Distribution of the short circuit time for different wire feed rates at constant voltage setting

(U=16V): a) 52 mm/s; b) 68 mm/s; c) 85 mm/s; d) 93 mm/s; e) 102 mm/s; f) 106 mm/s; g) 120 mm/s.
Fig. 5.5  Distribution of the arc time for different wire feed rates at constant voltage setting ($U=16V$): a) 52 mm/s; b) 68 mm/s; c) 85 mm/s; d) 93 mm/s; e) 102 mm/s; f) 106 mm/s; g) 120 mm/s.
Fig. 5.6 Distribution of the short circuit frequency for different wire feed rates at constant voltage setting
(U=16V): a) 52 mm/s; b) 68 mm/s; c) 85 mm/s; d) 93 mm/s; e) 102 mm/s; f) 106 mm/s; g) 120 mm/s.
5.3. Standard deviation of process parameters as criterion for process stability

As shown in the foregoing, the short circuiting GMAW process can be adequately described in terms of three parameters: the arc time, the short circuit time and the short circuit frequency. The variation of these parameters or, more specifically, the standard deviation reflects the regularity of the process and will therefore be an adequate measure of the process stability. The standard deviations of the arc time, the short circuit time and the short circuit frequency are given in Figs. 5.7-5.9, as function of the wire feed rate at constant voltage setting (U=16V). The values used in these figures are obtained from the distributions given in the previous section. It can be seen that the standard deviations of the arc time and the short circuit frequency reach a minimum at the same value of the wire feed rate. At this value the stability of the process is maximum.

It is important to note that the minimum in the standard deviation of the arc time and the short circuit frequency (and, hence, the maximum in process stability) corresponds to:

• optimal bead appearance (see chapter 2),
• a maximum in depth of penetration (see chapter 2),
• a minimum in arc time (see chapter 2),
• a maximum in short circuiting frequency (see chapter 2),
• a maximum in melting efficiency (see chapter 3),
• a minimum in mass transferred per short circuit (see chapter 4),
• a minimum in spatter loss (see chapter 4).

On the basis of the foregoing it can be concluded that at a certain voltage setting maximum process stability is achieved for a specific value of the wire feed rate. This is indicated by the thick dashed line in Fig. 5.10.

Conditions of maximum process stability were also determined for other values of the voltage. This results in a locus of maximum process stability in the voltage - wire feed rate diagram, as illustrated in Fig. 5.11. The process conditions for which maximum process stability occurs are referred to as optimal welding conditions.

The results presented above can be compared with those obtained by Liu et al. [5.2]. These authors describe metal transfer during short circuiting arc welding in terms of droplet rate and depict their results, for welding under 98% Ar - 2% O₂ gas shielding, in a voltage-current diagram as droplet rate isopleths, see Fig. 5.12. Although the droplet rate is relatively low, the trend of their observations is similar to that of the present investigation.
Fig. 5.7 Standard deviation of the arc time as function of the wire feed rate ($U=16\text{V}$).

Fig. 5.8 Standard deviation of the short circuit time as function of the wire feed rate ($U=16\text{V}$).

Fig. 5.9 Standard deviation of the short circuit frequency as function of the wire feed rate ($U=16\text{V}$).
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**Fig. 5.10**  Schematic presentation of the most important parameters of short circuiting arc welding as function of the wire feed rate at constant voltage setting. The thick dashed line represents the operating point of maximum process stability.
Stability of the Short Circuiting GMA Welding Process

Fig. 5.11  Schematic presentation of the short circuit operating area in the voltage - wire feed rate diagram. Maximum process stability occurs in a narrow zone around a locus indicated by the dashed line.

Fig. 5.12  Droplet rate isopleth for welding with 98% Ar - 2% O₂ gas shielding [5.2].
5.4. Optimal welding conditions

In order to obtain information about the process behaviour along the locus of optimal welding conditions, defined in the previous section, an additional series of experiments was carried out. In this series of experiments voltage and wire feed rate were simultaneously changed and tuned to optimal conditions. In each experiment measurements were made of the most important process parameters. The results are presented as function of the heat input, which is determined by the voltage, the current and the travel speed (see chapter 1). For the sake of simplicity the process efficiency is assumed to be unity.

Figure 5.13 shows the distribution of the short circuit frequency under optimal welding conditions for different values of the heat input. It can be seen that the single peak in the short circuit frequency, associated with optimal welding conditions, gradually shifts towards lower frequencies when the heat input is increased. This shift in frequency is related to the increase in weld pool size, as will be shown in the next chapter.

The standard deviation of the short circuit frequency as function of the heat input is given in Fig. 5.14. It can be seen that the standard deviation remains at a relatively low level, especially in the case of low values of the heat input. The somewhat higher values of the standard deviation in the upper heat input range are an indication of more irregular weld pool behaviour observed under these conditions [5.14].

In Figs. 5.15 - 5.17 the arc time, the short circuit time, the short circuit frequency and the spatter loss are presented as function of the heat input for optimal welding conditions. It can be seen that with increasing heat input along the locus of maximum process stability (optimal welding conditions) the arc time increases, the short circuit time remains virtually constant and the short circuit frequency and the spatter loss decrease. As will be shown in the next chapter the observed behaviour can be explained in terms of weld pool size.
Fig. 5.13  Distribution of the short circuit frequency in the case of welding under optimal welding conditions for different values of the heat input: a) 0.350 kJ/mm; b) 0.422 kJ/mm; c) 0.488 kJ/mm; d) 0.548 kJ/mm; e) 0.624 kJ/mm; f) 0.750 kJ/mm.
Fig. 5.14  Standard deviation of the short circuit frequency as function of the heat input for optimal welding conditions.

Fig. 5.15  Arc time (○) and short circuit time (●) as function of the heat input for optimal welding conditions.

Fig. 5.16  Short circuit frequency as function of the heat input for optimal welding conditions.

Fig. 5.17  Spatter loss as function of the heat input for optimal welding conditions.
5.5. Conclusions

On the basis of the results presented in this chapter, the following conclusions can be drawn. The stability of the short circuiting welding process can be described by the distributions of specific process parameters and/or the standard deviation of these parameters. Under stable welding conditions the distribution of the arc time and the short circuit frequency shows a single peak, whereas the standard deviations of these parameters reach a minimum. This minimum corresponds to:

• optimal bead appearance,
• a maximum in depth of penetration,
• a minimum in arc time,
• a maximum in short circuiting frequency,
• a maximum in melting efficiency,
• a minimum in mass transferred per short circuit,
• a minimum in spatter loss.

Based on the foregoing it is possible to assign a locus of optimal welding conditions in the voltage - wire feed rate diagram where the process stability is maximum. It should be realised that the position this zone shifts when the welding parameters are changed.
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References


Chapter 6

The role of weld pool oscillation during short circuiting GMA welding

6.1. Introduction

An important feature of short circuiting GMA welding is the occurrence of weld pool oscillations. These oscillations are triggered by the rupture of the liquid bridge at the end of the short circuit period and have a considerable effect of the process behaviour. In this chapter various aspects of weld pool oscillations will be discussed and special attention will be given to the relation between the oscillation frequency and the stability of the welding process.

6.2. Weld pool oscillation during GMA welding

The phenomenon of weld pool oscillation has been studied in detail by Xiao [6.1] in the case of GTA welding. A weld pool can be brought into natural oscillation and the oscillation frequency is related to weld pool geometry and physical properties of the liquid metal (surface tension and density). The weld pool oscillation can be easily triggered by fast changes of the arc pressure, for instance induced by low frequency short arc current pulses superimposed on the welding current. The oscillation frequency can be measured by monitoring the arc voltage variation since the arc voltage is related to the arc length. It appears that several modes of oscillation can be distinguished, depending on the welding
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conditions (in particular the peak current duration and the travel speed). It was found that for each of these oscillation modes a relation exists between the oscillation frequency and the dimensions of the weld pool. In this respect, a clear distinction should be made between oscillation in partially penetrated and in fully penetrated weld pools.

In partially penetrated weld pools two different modes of oscillation can occur. Mode 1 oscillation can be described in terms of an up and down motion of the weld pool surface. During the current pulse, the centre of the weld pool surface is indented by the arc pressure until equilibrium is reached with the counteracting gravity force and surface tension. When the arc pressure is abruptly reduced (end of the current pulse) the surface moves back to its original position, which is followed by overshoot and, hence, results in oscillation.

The other mode of oscillation in partially penetrated weld pools, referred to as mode 2 oscillation, is characterised by a front to back motion of the liquid metal. Mode 2 oscillation can be easily generated when the arc has an asymmetrical position with respect to the weld pool, as is the case during travelling arc welding at high travel speed. Mode 1 oscillation and mode 2 oscillation in partially penetrated weld pools are depicted schematically in Figs. 6.1 a and 6.1 b, respectively.

In fully penetrated weld pools only one dominant mode of oscillation (mode 3) occurs. This mode of oscillation can be compared with the oscillation of a stretched membrane, see Fig. 6.1 c. The oscillation frequency of mode 3 is much lower than those of mode 1 and mode 2. The abrupt change in oscillation frequency when a transition occurs from partial penetration to full penetration or vice versa can be used as a powerful tool in penetration control of the GTA welding process [6.2].

Weld pool oscillation also occurs during short circuiting GMA welding [6.3, 6.4]. In this case oscillation of the weld pool is triggered by the momentum of the liquid metal injected into the weld pool at the moment of rupture of the liquid bridge between the electrode and the weld pool and by the abrupt generation of arc pressure directly after arc reignition. The arc pressure is proportional to the square of the arc current.

Defize et al. [6.5] and Smith [6.6, 6.7] mention the momentary high current arc, immediately following a short circuit, as the cause of depression of the weld pool, which has risen due to the absence of arc pressure during the short circuit period. In a correctly operating short circuiting arc welding process this has the effect of producing an oscillating weld pool, which rises to meet the advancing electrode tip.

Dorn et al. [6.3] describe the metal transfer mechanism in terms of a mechanical resonant circuit. In their view the oscillation ripple moves in outward direction and is reflected by the edge of the weld pool. The reflected wave travels back to the weld pool centre underneath the
electrode where it contacts the droplet. The authors state that the shielding gas composition influences the weld pool oscillation. For example during CO₂ welding the weld pool oscillation is very irregular compared to the weld pool motion during welding with Ar-CO₂ as shielding gas.

Lancaster [6.4] considers the situation of fully penetrated weld pools and argues that regular periodicity of operation is accompanied by a minimal amount of spatter. This situation is reached when the frequency of arc current oscillation (i.e. short circuit frequency) is synchronised with the natural frequency of oscillation of the weld pool surface.

Maruo et al. [6.8] modelled oscillations of fully penetrated weld pools in the case of pulsed current arc welding. They found that the weld pool oscillates in accordance to the cyclic variation in welding current. The oscillation is related to the onset of spattering and to the arc stability during short circuiting arc welding.

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**Fig. 6.1** Top view and side view of weld pool oscillation modes: a) mode 1, partial penetration; b) mode 2, partial penetration; c) mode 3, full penetration.
At this point some remarks should be made concerning the differences between GTA and GMA weld pool oscillation.

First of all, it should be mentioned that measuring of weld pool oscillations by monitoring the variation in arc voltage is virtually not possible in GMA welding. Voltage fluctuations due to weld pool oscillations are extremely difficult to separate from voltage variations as a result of droplet growth, shifting of the contact area between the arc and the electrode tip and variations in the contact point between the electrode wire and the contact tube.

Another difference in weld pool behaviour between GTA and GMA welding is due to the chemical composition of the shielding gas. GTA welding is carried out with an inert shielding gas, whereas during GMA welding of mild steel, normally CO2 or Ar - CO2 gas mixtures are used. The oxidising component of the shielding gas influences the arc behaviour and the surface tension of the liquid metal and, therefore, the oscillation behaviour.

Because during GMA welding a consumable electrode wire is used, metal transport will occur and this will influence weld pool oscillation. Kapadia [6.9] states in an editorial review that because of this, the evaluation of the weld pool motion is much more problematic in the case of GMA welding than in the case of GTA welding. The momentum of liquid metal transferred to the weld pool acts as a trigger of weld pool oscillation, but can also distort the oscillation. Furthermore, as filler metal is added to the weld pool, the surface of the weld pool in the equilibrium situation will not be flat, but will show a slight curvature. Indirect information about this curvature can be obtained from the solidified weld pool crater. However, high-speed films show that during welding the front part of the weld pool is relatively flat and is oscillating at the plate surface level [6.5].

The occurrence of a relatively large amplitude of vertical displacement in the tail of the weld pool is conflicting with the assumption, used in the derivation of the equations governing the weld pool oscillation, that the vertical displacement is small compared to the oscillation wavelength. However, high-speed films reveal that under optimal welding conditions the tail part of the weld pool hardly influences the oscillation behaviour of the front part of the pool. Furthermore, it must be kept in mind that near the weld pool boundary, where the penetration depth is small, the influence of gravity may not be neglected any more and capillary-gravity waves may become important [6.10]. Another point of interest is that weld pool penetration is affected by metal transfer [6.11, 6.12]. An axial stream of metal droplets creates a fingershape cross sectional area, where lack of fusion may occur near the weld bead boundary. Again, under optimal welding conditions lack of fusion is not observed and depth of penetration is maximal. Therefore, the equations governing the oscillation of the GTA weld pool can also be applied in the case of GMA welding.

Finally, the travel speed in the case of GMA welding is higher than in the case of GTA
welding. This has consequences for the oscillation behaviour, since the travel speed influences the geometry of the weld pool. In fact, a higher travel speed results in an elongated weld pool shape and shifts the centre of the weld pool in backward direction. The resulting eccentricity of the electrode with respect to the weld pool centre enhances the transition from mode 1 to mode 2 oscillation. Therefore, at high travel speed mode 2 oscillation may readily occur.

6.3. The oscillation frequency

As shown in Appendix B it is possible to calculate the oscillation frequency for the three different oscillation modes when taking a number of assumptions into account. This leads to the following equations:

\[
\begin{align*}
\text{mode 1} & \quad f_{o1} = 5.84 \left( \frac{\gamma}{\rho_l} \right)^{1/2} D^{-3/2} \\
\text{mode 2} & \quad f_{o2} = 3.37 \left( \frac{\gamma}{\rho_l} \right)^{1/2} D^{-3/2} \\
\text{mode 3} & \quad f_{o3} = 1.08 \left( \frac{\gamma}{H\rho_s} \right)^{1/2} D^{-1}
\end{align*}
\]  

(6.1) 

(6.2) 

(6.3)

in which \(f_{o1}, f_{o2}\) and \(f_{o3}\) are respectively the oscillation frequency of mode 1, mode 2 (partial penetration) and mode 3 (full penetration), \(\gamma\) represents the surface tension, \(\rho_l\) and \(\rho_s\) are respectively the density of the liquid and solid metal, \(H\) is the plate thickness, \(D\) is the equivalent weld pool width which is determined by the geometry of the weld pool, see Appendix B.

As can be seen in equations (6.1) to (6.3) the oscillation frequencies of the three modes are entirely determined by the surface tension of the liquid metal, the density and the geometry of the weld pool. These three factors are briefly discussed in Appendix C.

6.4. A criterion for maximum process stability

Considering the course of events taking place during the short circuiting arc welding process in combination with the oscillation of the weld pool, it must be expected that maximum
process stability occurs when the short circuit frequency \( f_s \) equals the oscillation frequency \( f_0 \) of the weld pool, i.e. when \( f_s = f_0 \). When this is the case, the oscillating surface of the weld pool touches the metal droplet formed at the end of the electrode wire once every oscillation cycle. It is evident that under these conditions the stability of the process is maximum, the short circuit cycle being dictated by the highly regular weld pool oscillation. High-speed film pictures reveal that under these welding conditions mode 1 oscillation plays the major role and mode 2 oscillation can be neglected.

At lower wire feed rates the short circuit frequency is smaller than the oscillation frequency of the weld pool \( (f_s < f_0) \). Under these conditions the oscillating weld pool surface will miss the growing droplet at the end of the electrode one or more times before contact is established. It is also possible that the weld pool starts to oscillate in mode 2. Both phenomena will result in a more random course of events (less constant values of arc time, short circuit frequency and transferred droplet mass), i.e. in lower process stability.

At higher wire feed rates the arc length becomes so small that stubbing of the electrode wire in the weld pool becomes a real possibility, distorting the weld pool oscillation and resulting in irregularities and instabilities of the welding process.

The sequence of events taking place during the short circuiting arc welding process as described in the foregoing, were found to be consistent with the results of high-speed filming.

6.5. Verification of the criterion

6.5.1. Partial penetration

In order to test the validity of the hypothesis that maximum process stability occurs when the short circuit frequency and the oscillation frequency of the weld pool are synchronised, welding experiments were carried out in which partially penetrated weld pools of different size were produced.

During each welding experiment the short circuit frequency was measured, whereas the oscillation frequency of the weld pool was calculated from the width of the weld pool with the help of the equation valid for mode 1 oscillation [6.1, 6.13]:

\[
f_{o1} = 5.84 \left( \frac{\gamma}{\rho_t} \right)^{1/2} D^{-3/2}
\]

(6.1)
The Role of Weld Pool Oscillation during Short Circuiting GMA Welding

Table 6.1 Physical properties of mild steel Fe 360 used for the calculation of $f_0$.

<table>
<thead>
<tr>
<th>material</th>
<th>surface tension (N/m)</th>
<th>density liquid metal (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe 360</td>
<td>0.9</td>
<td>$7.0 \times 10^3$ [6.14]</td>
</tr>
</tbody>
</table>

![Graph showing frequency (Hz) vs. wire feed rate (mm/s)](image)

Fig. 6.2 The measured short circuit frequency (●) and the calculated oscillation frequency (○) as function of the wire feed rate ($U=16$V).

where $\gamma$ represents the surface tension, $\rho$ the density of liquid steel and $D$ the weld pool width. The values of $\gamma$ and $\rho$ used for the calculation are listed in Table 6.1.

In a first series of experiments the voltage was kept constant while the wire feed rate was increased. Figure 6.2 shows the measured short circuit frequency and the calculated oscillation frequency as a function of the wire feed rate for a voltage setting of 16 V. It can be seen that the short circuit frequency increases and the oscillation frequency decreases with increasing wire feed rate and that both frequencies become approximately equal at the wire feed rate for which the short circuit frequency is maximum, i.e. under conditions of maximum process stability (see section 6.4).

For low wire feed rates the small weld pool oscillates with a relatively high frequency and it
takes several oscillation cycles before the short circuit contact is made. When the wire feed rate is increased the short circuit frequency distribution splits up in a double peak, see chapter 5. The high short circuit frequency appears to coincide with the calculated oscillation frequency of the weld pool. The low short circuit frequency indicates the failure of establishing contact between the weld pool and the droplet during the first oscillation cycle. With increasing wire feed rate the amplitude of the low short circuit frequency in the spectrum decreases in favour of the high frequency peak. When finally optimal welding conditions are reached a single high short circuit frequency remains which equals the calculated oscillation frequency of the weld pool.

Figure 6.3 shows the nominal value and the standard deviation of the low and high short circuit frequencies and the calculated oscillation frequency as function of the wire feed rate. During stubbing the wire feed rate is so high that no stationary situation can be reached. This results in random weld pool movements and a short circuit frequency which is physically not related with the calculated oscillation frequency.

![Graph showing frequency vs. wire feed rate](image)

**Fig. 6.3** Nominal value and standard deviation of the low (□) and high (○) short circuit frequencies and the calculated oscillation frequency of the weld pool (●) as function of the wire feed rate. ($U=16V$).

To further evaluate the criterion for maximum process stability as formulated in section 6.4, experiments were carried out under conditions of maximum process stability, i.e. under conditions where the average short circuit frequency is maximum. Weld pool dimensions were changed by variation of current and voltage simultaneously along the locus of
maximum process stability. In Fig. 6.4 the measured short circuit frequency (experimental points) and the calculated oscillation frequency of the weld pool (solid line) for conditions of maximum process stability are presented as a function of weld pool width. As expected (see equation (6.1)) the short circuit frequency decreases with increasing weld pool width. For low values of the weld width relatively good agreement exists between the average short circuit frequency and the oscillation frequency. However, for broader weld pools the short circuit frequency becomes slightly higher than the calculated oscillation frequency.

The results shown in Fig. 6.4 are presented in another way in Fig. 6.5. In this figure the calculated oscillation frequency is plotted as a function of the measured short circuit frequency. The straight line in the figure represents the situation of maximum process stability, i.e. \( f_s = f_0 \).

![Graph](image)

*Fig. 6.4 The measured short circuit frequency (●) and the calculated oscillation frequency (solid line) as function of the weld pool width for conditions of maximum process stability.*
Fig. 6.5  The calculated oscillation frequency versus the measured short circuit frequency for conditions of maximum process stability.

The observed difference between $f_s$ and $f_0$ can be understood by taking the influence of the weld pool temperature on the surface tension into account. With this in mind the surface tension was adapted in such a way that the oscillation frequency of the weld pool would equal the measured short circuit frequency. Figure 6.6 shows the adapted values of the surface tension as function of the heat input. It can be seen that the surface tension increases with heat input (temperature). This is in agreement with the results obtained by Xiao et al. [6.15] and Keene [6.16]. Thus, by taking the temperature dependence of the surface tension into account the solid line representing the oscillation frequency in Fig. 6.4 can be shifted towards the experimental points representing the short circuit frequency.
Experiments were also carried out in which weld pool dimensions were altered by varying the travel speed. The results are presented in Figs. 6.7 and 6.8. Again relatively good agreement is found between the measured short circuit frequency and the calculated oscillation frequency of the weld pool.
Chapter 6

A third set of welding experiments was performed using shielding gases of different composition (argon based mixtures containing increasing amounts of CO₂). As is shown in Appendix C, the surface tension of liquid weld metal depends strongly on the oxygen concentration. A higher CO₂ content in the shielding gas results in higher oxygen concentrations in the weld metal, which decreases the surface tension considerably [6.17]. Furthermore, with increasing oxygen concentrations in the weld metal, the temperature dependence of the surface tension (\(\delta\gamma/\delta T\)) will change [6.16].

For each shielding gas the optimal welding conditions were determined by varying the voltage while the wire feed rate was kept constant. For the different optimal situations the short circuit frequency was determined, whereas the corresponding oscillation frequency was calculated using equation (6.1). The value of the surface tension used in the calculations was 0.9 N/m. The results obtained are presented in Fig. 6.9.

The figure shows that good agreement exists between the short circuit frequency and the oscillation frequency for CO₂ percentages above 20%. This implies that at higher CO₂ contents the surface tension remains constant.

This can be understood when considering the influence of the temperature. As a result of the increase in CO₂ content, the position of the locus of optimum welding conditions will shift towards higher values of voltage. Due to this shift the heat input, and thus the temperature of the weld metal, increases. This results in an increase of the surface tension of the liquid metal, as \(\delta\gamma/\delta T\) is positive. Apparently, the influence of the increased oxygen concentration on the surface tension and that of the higher temperature compensate each other.

The difference between the short circuit frequency and the oscillation frequency at low CO₂ percentages in the shielding gas is attributed to the shape of the weld pool. Under these conditions the penetration of the weld in the base metal is minimal and a high weld bead profile (high wetting angle) is observed, which implies that equation (6.1) is not valid any more.

It should be noted that in the case of both low and high CO₂ content in the shielding gas, the stability of the process is relatively low, which is expressed by a higher standard deviation of the short circuit frequency. In agreement with this, Dorn et al. [6.3] observed irregular movement of the weld pool during welding with high CO₂ content in the shielding gas, which causes a destabilisation of the process.

On the basis of the results presented above it can be concluded that maximum process stability occurs when the short circuit frequency and the mode 1 oscillation frequency of the weld pool are synchronised. The validity of this conclusion is demonstrated by Fig. 6.10 in which the results of the measured short circuit frequency and the calculated oscillation frequency obtained under optimal welding conditions are plotted for all experiments.
Fig. 6.9  The measured short circuit frequency (●) and the calculated oscillation frequency of the weld pool (○) as function of the CO₂ content of the shielding gas. The value of the surface tension used in the calculation was 0.9 N/m.

Fig. 6.10  The calculated oscillation frequency versus the measured short circuit frequency under optimal welding conditions for all experiments.
6.5.2. Full penetration

As discussed in section 6.2, full penetration during GTAW is accompanied by mode 3 oscillation, which shows similarities with the oscillation of a stretched membrane. However, a minimum bottom weld pool width is necessary for mode 3 to occur. For small values of the bottom diameter ($D_b$) with respect to the top diameter ($D_t$) the weld pool is supported by the solid boundary and therefore still oscillates in the partial penetration mode (mode 1). At a certain value of $D_b$ a transition from mode 1 to mode 3 occurs, having a much lower oscillation frequency and a larger amplitude, see Fig. 6.11. Xiao [6.1] found that in the case of GTAW of both mild steel (Fe 360) and stainless steel (AISI 316) the transition to mode 3 oscillation occurs when the ratio $D_b/D_t$ (bottom diameter of the weld pool/ top diameter of the weld pool) is about 0.5. Yoo et al. [6.18] also studied the transition from partial to full penetration and concluded that this transition occurs when the bottom pool surface area is 0.3 to 0.5 times the top pool surface area. Under these conditions the high frequency signal associated with partial penetration oscillation was found to disappear.

![Graph](image)

*Fig. 6.11 Oscillation frequency of fully penetrated weld pool under travelling arc conditions as a function of the diameter of the bottom surface [6.1].*
The Role of Weld Pool Oscillation during Short Circuiting GMA Welding

In the case of mode 3 oscillation the relation between the oscillation frequency of the weld pool and the weld pool diameter is given by the following equation [6.1]:

\[ f_{o3} = 1.08 \left( \frac{\gamma}{H \rho_s} \right)^{1/2} D^{-1} \]  \hspace{1cm} (6.3)

in which \( \gamma \) represents the surface tension of the liquid metal, \( H \) the plate thickness, \( \rho_s \) the density of the solid metal and \( D \) the diameter of the cylinder the volume of which is equal to the volume of the tapered weld pool. \( D \) can be expressed in terms of top (\( D_t \)) and bottom (\( D_b \)) weld pool diameter with the help of the following equation:

\[ D^2 = \frac{1}{3} \left( D_t^2 + D_t D_b + D_b^2 \right) \]  \hspace{1cm} (6.4)

In the case of full penetration the oscillation frequency decreases abruptly when the transition criterion for mode 3 oscillation is reached. Thus, measuring weld pool oscillation on line during welding makes it possible to monitor and control weld pool penetration.

An important question in relation to the present work is whether mode 3 oscillation does also occur in the case of short circuiting GMA welding. Lancaster [6.4] expects mode 1 oscillation to occur in the case of full penetration during short circuiting GMA welding and proposes the following equation for the oscillation frequency:

\[ f = \frac{1}{2\pi} \left( \frac{\gamma}{\rho_s h r^2} \right)^{1/2} j_{0,2} \]  \hspace{1cm} (6.5)

with \( j_{0,2} \) the second root of the Bessel function of the first kind, \( r \) the radius of the weld pool and \( h \) the plate thickness. It is assumed that during the arc period only part of one oscillation is completed before the next short circuit occurs. Furthermore, the influence of the surface tension at the bottom side of the weld pool is neglected. On this basis he calculates an oscillation frequency of 62.3 Hz (corresponding with an arc time of approximately 7.5 ms). If the surface tension of the bottom of the weld pool is taken into account, an oscillation frequency of 88.1 Hz is found (arc time 5.6 ms).

Matsunawa [6.19] calculated the maximal bottom width for self support of the weld pool as function of the plate thickness. Assuming a flat top surface and a cylindrical pool shape, the following equation gives an approximation of the maximum allowable bottom width:
Chapter 6

\[
D_{\text{burn}} = \frac{2\gamma}{\rho gh}
\]  

Equation (6.6) shows that the maximum allowable width for self support of the molten pool (\(D_{\text{burn}}\)) decreases inversely proportional with plate thickness (h).

To assist the support of the weld pool and to prevent burn-through, several weld bead backing systems are used in practice, such as solid backing (ceramic strips), flux and gas backing or a combination of these methods. It appears that the maximum allowable width for self support is larger in an argon backing atmosphere than in an oxidising backing gas, because in the case of argon the surface tension is higher. It is evident that in the case of solid backing mode 3 oscillation is not possible.

It should be noted that when the reinforcement of the weld is taken into account, the effective height (the corrected plate thickness, \(h_{\text{eff}}\)) in equation (6.6) increases, which results in a reduction of the maximum allowable width for self support of the molten pool. Furthermore, the impact of the transferring metal has a negative effect on the maximum bottom width.

This implies that there is a possibility that the conditions for mode 3 oscillation will not be reached, because burn-through will occur beforehand.

Another reason for doubting the possibility of obtaining mode 3 oscillation is the fact that, as a result of the metal transfer to the weld pool, the weld pool top width is relatively large. This strongly reduces the possibility to fulfil the requirements of full penetration.

To explore the possibility of a mode switch (from mode 1 to mode 3) during GMAW, a number of experiments was carried out. These experiments were carried out on a workpiece with a semi-V groove geometry, see Fig. 6.12, in order to avoid a large reinforcement. In order to realise a transition from partial penetration to full penetration the voltage and the current (and thus the heat input) were simultaneously increased to maintain optimal welding conditions. The short circuit frequency was measured and the oscillation frequency of the weld pool was calculated by means of equation (6.1). The results are presented in Table 6.2 and in Fig. 6.13 and show that no mode switch occurs up till the situation that burn-through takes place. The results are in good agreement with the criteria proposed by Xiao [6.1] and by Yoo et al. [6.18], \(D_{\text{min}} / D_t > 0.5\).

The fact that burn-through (BT) was observed at the highest value of the heat input (last part of the weld) is consistent with the criterion proposed by Matsunawa [6.19], \(D_{\text{min}} > D_{\text{burn}}\).
Table 6.2  Experimental results of the semi V-groove experiments ($\gamma = 0.9 \text{ N/m}$).

<table>
<thead>
<tr>
<th>heat input (kJ/mm)</th>
<th>$f_s$ (Hz)</th>
<th>st dev $f_s$ (Hz)</th>
<th>$f_{01}$ (Hz)</th>
<th>$h_{\text{eff}}$ (mm)</th>
<th>$D_t$ (mm)</th>
<th>$D_{\min}$ (mm)</th>
<th>$D_{\min}/D_t$</th>
<th>$D_{\text{burn}}$ (mm)</th>
<th>mode</th>
<th>BT</th>
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<tr>
<td>0.447</td>
<td>107</td>
<td>14</td>
<td>117</td>
<td>5.73</td>
<td>6.82</td>
<td>1.36</td>
<td>0.20</td>
<td>4.6</td>
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</tr>
<tr>
<td>0.475</td>
<td>108</td>
<td>9</td>
<td>112</td>
<td>6.03</td>
<td>7.05</td>
<td>2.12</td>
<td>0.30</td>
<td>4.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.510</td>
<td>104</td>
<td>9</td>
<td>111</td>
<td>6.15</td>
<td>7.10</td>
<td>2.35</td>
<td>0.33</td>
<td>4.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.570</td>
<td>100</td>
<td>16</td>
<td>99</td>
<td>6.08</td>
<td>7.65</td>
<td>2.21</td>
<td>0.29</td>
<td>4.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.632</td>
<td>95</td>
<td>43</td>
<td>101</td>
<td>7.62</td>
<td>7.55</td>
<td>3.41</td>
<td>0.45</td>
<td>3.4</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

Fig. 6.12  Workpiece geometry (a) and shape of the weld (b).
Fig. 6.13 The measured short circuit frequency (○) and the calculated oscillation frequency of the weld pool (●) as function of the heat input, semi-V-groove experiments.

6.6. Conclusions

From the results presented in this chapter the following conclusions can be drawn.

- Weld pool oscillations are triggered by the reignition of the arc after the rupture of the liquid bridge and by the momentum of liquid metal transferred and play an important role as regards the stability of the short circuiting welding process.
- A distinction can be made between different modes of oscillation. The oscillation frequencies of these modes are influenced by the physical properties of the liquid material (surface tension and density of the liquid) and by the dimensions of the weld pool.
- In the case of partially penetrated weld pools optimal welding conditions and maximum process stability occur when the oscillation frequency and the short circuit frequency are equal. Under these conditions contact is established between the weld pool surface and the pendant droplet during each oscillation of the weld pool.
- When passing from partial penetration to full penetration no abrupt change in weld pool oscillation frequency is observed due to the occurrence of premature burn-through.
The Role of Weld Pool Oscillation during Short Circuiting GMA Welding

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Appendix A

Calorimetric measurements

In chapter 3 experiments are described in which use is made of a calorimeter in order to measure the heat flow to the workpiece [A.1, A.2]. The experimental set-up used for these measurements is shown in Fig. A.1 [A.3]. The calorimeter consists of a stainless steel water compartment, on which the workpiece was mounted. The workpiece, a mild steel metal strip (250x50x5mm), was fixed by means of 6 clamps. An O-ring was used to seal off the water compartment. The bottom of the workpiece strip was in direct contact with the water in the container. Before the start of each experiment a water pre-flow was established, in order to supersede gas bubbles and to create a stationary water flow. The water inlet and outlet are located respectively near the beginning and the end of the workpiece. The water flow was measured before entering the workpiece by means of a Reed contact and a Schmitt trigger. The water flow meter was calibrated before the measurements. The difference between inlet and outlet water temperature was determined by means of two temperature sensors. During the experiments the temperature difference was measured and the measurement was stopped when after welding the inlet and outlet temperature had become equal. The frequency of the temperature measurement was 250 Hz. The collected data was filtered and averaged over a period of 2 s. The data of the water flow and the temperature difference was stored on computer and analysed. In this way, the total additional heat content and thus the heat flow to the workpiece was determined.
Fig. A.1  *Schematic representation of the calorimeter: a) top view and b) side view.*

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Appendix B

Weld pool oscillations

B.1. Introduction

As mentioned in chapter 6, oscillations are introduced in the weld pool, by the sudden change in arc pressure at the moment of reignition of the electric arc and by the momentum of the mass transfer. Three major modes of oscillations were observed in the case of GTAW [B.1, B.2]. Oscillation modes 1 and 2 occur in partially penetrated weld pools. Mode 3 is encountered in the case of full penetration. For the sake of completeness the three modes of weld pool oscillation are once more depicted in Fig. B.1.

In this appendix the theory of weld pool oscillation is briefly reviewed.

B.2. General equations

Using the principles of hydrodynamics, a description can be given of the liquid motion in a circular pool of liquid metal with diameter (D) and an uniform depth (h), which is brought into oscillation by an external force. This is schematically depicted in Fig. B.2.

For modelling weld pool oscillations, the following assumptions are made:
- the liquid metal is incompressible and inviscid,
- the surface of the pool is flat in the equilibrium situation,
- the wall of the pool is rigid,
- the motion of the liquid in the pool is irrotational, the vorticity is zero (potential flow).
Appendix B

<table>
<thead>
<tr>
<th>top view</th>
<th>side view</th>
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<tbody>
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<td><img src="image" alt="Diagram" /></td>
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<td><img src="image" alt="Diagram" /></td>
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</table>

Fig. B.1  Top view and side view of weld pool oscillation modes: a) mode 1, partial penetration; b) mode 2, partial penetration; c) mode 3, full penetration.

Fig. B.2  Schematic presentation of the liquid motion in a circular pool with uniform depth.
The motion of liquid metal can be described by the Laplace equation [B.1 - B.3]:

\[ \Delta \Phi = 0 \]  \hspace{1cm} (B.1)

In cylindrical co-ordinates the motion can be expressed as:

\[ \frac{\partial^2 \Phi}{\partial r^2} + \frac{1}{r} \frac{\partial \Phi}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \Phi}{\partial \theta^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0 \]  \hspace{1cm} (B.2)

in which \( \Phi \) is the velocity potential of the motion and \( r \), \( \theta \) and \( z \) are the cylindrical co-ordinates.

The following boundary conditions should be satisfied:
- at the container bottom the velocity of the liquid metal is zero:
  \[ \frac{\partial \Phi}{\partial z} = 0, \ z = h \]  \hspace{1cm} (B.3)
- the velocity potential is zero at the boundary of the pool:
  \[ \Phi = 0, \quad r = \frac{D}{2} \]  \hspace{1cm} (B.4)

The solution of differential equation (B.2) will be derived below for three situations:
- a circular partially penetrated weld pool,
- an elliptical partially penetrated weld pool,
- a fully penetrated weld pool.

**B.3. Partial penetration (circular weld pool)**

As the motion is assumed to be irrotational, \( \frac{\partial^2 \Phi}{\partial \theta^2} = 0 \), equation (B.2) can be simplified to:

\[ \frac{\partial^2 \Phi}{\partial r^2} + \frac{1}{r} \frac{\partial \Phi}{\partial r} + \frac{\partial^2 \Phi}{\partial z^2} = 0 \]  \hspace{1cm} (B.5)
Appendix B

This differential equation can be solved by separation of variables, resulting in the general solution:

\[ \Phi = AJ_0(kr)(B_1e^{kz} + B_2e^{-kz})\cos(\omega t + \omega_0) \]  

(B.6)

in which \( A, B_1, B_2 \) (\( B_1 = B_2e^{-2kh} \)), \( \omega_0 \) are constants, \( k \) is the wave number, \( J_0 \) is the first kind zero order Bessel function and \( \omega \) is the angular oscillation frequency.

A pressure difference between both sides of the surface of the liquid causes a deviation from the equilibrium position of the surface. The vertical displacement of the surface with respect to the equilibrium position is denoted as \( \xi \). The Laplace equation describes the curvature of the liquid as function of the pressure difference between the two sides of the surface [B.3]:

\[ p - p_0 = -\gamma \left( \frac{1}{r} \frac{\partial \xi}{\partial r} + \frac{\partial^2 \xi}{\partial r^2} \right) \]  

(B.7)

with \( p \) the pressure in the fluid near the surface, \( p_0 \) the external pressure and \( \gamma \) the surface tension.

Since the amplitude of the oscillation is small, the vertical component of the velocity of points on the surface is approximately the time derivative of the displacement (the normal component of the fluid velocity at the surface must be equal to the velocity of the surface itself). This means that:

\[ \frac{\partial \xi}{\partial t} = \left( \frac{\partial \Phi}{\partial z} \right)_{z=\xi} \]  

(B.8)

The pressure at the surface of the liquid \( (p) \) for potential flow can be expressed as:

\[ p = -\rho l g \xi - \rho l \frac{\partial \Phi}{\partial t} \]  

(B.9)

with \( \rho_l \) the density of the liquid metal and \( g \) the gravitational constant.

Substituting equations (B.8) and (B.9) into equation (B.7) gives:

\[ \rho l \frac{\partial \Phi}{\partial z} + \rho l \frac{\partial^2 \Phi}{\partial t^2} - \gamma \frac{\partial}{\partial z} \left( \frac{1}{r} \frac{\partial \Phi}{\partial r} + \frac{\partial^2 \Phi}{\partial r^2} \right) = 0 \quad \text{for} \quad z = 0 \]  

(B.10)
Differentiating the velocity potential (B.6) with respect to t, z and r and substitution into equation (B.10), finally results in the angular oscillation frequency of the weld pool ($\omega$).

$$\omega^2 = \left( gk + \frac{\gamma}{\rho_l} k^3 \right) \tanh(2kh)$$  \hspace{1cm} (B.11)

The first term between brackets represents the influence of the gravity, while the second term stands for the capillary action. The term $\tanh(2kh)$ accounts for the depth of the weld pool.

The wave number $k$ is dependent on the mode of oscillation. To fulfil the boundary condition (B.4) it is necessary that:

$$J_0\left(\frac{kD}{2}\right) = 0$$  \hspace{1cm} (B.12)

with $J_0$ the first kind zero order Bessel function.

In the case of mode 1 oscillation, the corresponding root of the Bessel function is $kD/2 = 5.52$ [B.4]. With $f_o = \omega/2\pi$, equation (B.12) for mode 1 oscillation becomes:

$$\text{mode 1} \quad f_{o1}^2 = \frac{1}{4\pi^2} \left( \frac{11.04}{D} g + \frac{1345.5}{D^3} \frac{\gamma}{\rho_l} \right) \tanh\left( \frac{22.08 h}{D} \right)$$  \hspace{1cm} (B.13)

It appears that the influence of gravity may be neglected when the amplitude is small. The term $\tanh(22.08h/D)$ lies close to 1 for the geometry investigated. In other words, the bottom of the weld pool does not influence the oscillation behaviour. Therefore, equation (B.13) can be simplified to:

$$\text{mode 1} \quad f_{o1} = 5.84 \left( \frac{\gamma}{\rho_l} \right)^{1/2} D^{-3/2}$$  \hspace{1cm} (B.14)
Appendix B

B.4. Partial penetration (elliptical weld pool)

In a similar way the oscillation frequency for mode 2 oscillation for travelling arc welding is derived. However, the pool is not circular and thus $\frac{\partial^2 \Phi}{\partial \theta^2} = 0$ is not valid. Therefore, the general solution of the Laplace equation is somewhat more complicated:

$$\Phi = AJ_n(kr)\left(B_1 e^{kz} + B_2 e^{-kz}\right)\cos(\omega t + \omega_0) \cos(n\theta + \theta_0)$$  \hspace{1cm} (B.15)

with $J_n$ the first kind $n^{th}$ order Bessel function. Only $J_0$ and $J_1$ are important with regard to the real situation of a partially penetrated weld pool.

The solution of equation (B.15) is similar to the solution of equation (B.6). However, the value of $k$ is different and determined by $J_n\left(\frac{k D}{2}\right) = 0$, with $D$ the equivalent diameter of the elongated weld pool (the diameter of a circle with an area which equals the surface area of the elongated weld pool). The root of the Bessel function corresponds with $k = 7.66/D$ [B.4]. This results in the following equation:

$$f^2 = \frac{1}{4\pi^2} \left(\frac{7.66}{D} g + \frac{449 \gamma}{D^3 \rho_l} \right) \tanh \left(15.32 \frac{h}{D}\right)$$ \hspace{1cm} (B.16)

Again, the influence of the gravitational term is neglected and $\tanh(15.32h/D)$ is replaced by 1. This yields the following equation for the frequency of the mode 2 oscillation:

$$f_{\omega 2} = 3.37 \left(\frac{\gamma}{\rho_l}\right)^{1/2} D^{-3/2}$$ \hspace{1cm} (B.17)

B.5. Full penetration

In the case of full penetration the situation is principally different. The mode of oscillation can be compared with the oscillation of a stretched membrane, expressed by a two-dimensional wave equation [B.5]:

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\[
\frac{\partial^2 \Phi}{\partial t^2} = \frac{2\pi r^2 \gamma}{\pi r^2 H \rho_l} \Delta \Phi \tag{B.18}
\]

with \(2\pi r^2 \gamma\) the surface energy of the fully penetrated weld pool and \(\pi r^2 H \rho_l\) the mass of the liquid metal in the weld pool. Assuming a symmetrical motion in a circular weld pool, the general solution of equation (B.18) can be described by:

\[
\Phi = AJ_0(kr) \cos \left( k \left( \frac{2\pi r^2 \gamma}{\pi r^2 H \rho_l} \right)^{1/2} t + C \right) \tag{B.19}
\]

In this equation \(A\) and \(C\) represent constants.

The lowest order harmonic mode oscillation satisfies:

\[
k \left( \frac{2\pi r^2 \gamma}{\pi r^2 H \rho_l} \right)^{1/2} T = 2\pi \tag{B.20}
\]

with \(T\) the period of oscillation.

To satisfy the boundary conditions \(kr\) should be equal to 2.405, the lowest order root of \(J_0\) [B.4].

This finally yields the following equation, which is used for calculating the oscillation frequency of fully penetrated weld pools (mode 3 oscillation):

\[
f_{o3} = 1.08 \left( \frac{\gamma}{H \rho_s} \right)^{1/2} D^{-1} \tag{B.21}
\]

In the realistic case of a non-cylindrical weld pool \(D\) represents the equivalent diameter (the diameter of the cylinder the volume of which is equal to the volume of the weld pool).
Appendix B

B.6. Accuracy of the frequency calculation

The relative error in the calculated value of the oscillation frequency (equations B.14 and B.17) can be determined by the following equation:

$$\frac{\Delta f_o}{|f_o|} = \frac{1}{2} \frac{\Delta \gamma}{|\gamma|} + \frac{1}{2} \frac{\Delta \rho}{|\rho|} + \frac{3}{2} \frac{\Delta D}{|D|}$$  \hspace{1cm} (B.22)

Assuming the uncertainty in the surface tension $\Delta \gamma = 0.1$ N/m, in the density of liquid steel $\Delta \rho = 0.2 \times 10^3$ kg/m$^3$ and in the measurement of the weld pool diameter $\Delta D = 0.25$ mm, and taking for the surface tension $\gamma = 0.9$ N/m, for the density of liquid steel $\rho = 7.0 \times 10^3$ kg/m$^3$ and for the weld pool diameter $D = 5$ to 10 mm, the error in the oscillation frequency lies between 10% and 14%. This error is somewhat larger than the error in the measured short circuit frequency (4%).

Xiao [B.1] calculated the relative error due to the assumption that the term representing the gravity force in equation B.14 is neglected and found that this relative error is smaller than 3% in the case of a weld pool width smaller than 10 mm. Furthermore, the terms $\tanh(22.08h/D)$ and $\tanh(15.32h/D)$ are approximately equal to 1, in other words the oscillation frequency is virtually independent of weld pool depth.

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Appendix C

Factors influencing weld pool oscillation

C.1. Surface tension of liquid metals

The surface tension of liquid metals is influenced by different factors: the chemical composition of the liquid metal, the chemical composition of the welding atmosphere and the temperature. These factors will be briefly discussed below together with the various experimental measuring techniques.

Generally speaking, the chemical composition of the liquid metal has a significant influence on the surface tension. Especially surface active elements as oxygen and sulphur play an important role in this respect. Keene [C.1] gives a review of data for the surface tension of iron and its binary alloys. Figure C.1 shows the surface tension of liquid iron as a function of the oxygen concentration. As can be seen, a wide scatter in surface tension values is found, depending on temperature and experimental method.

Of special interest is the influence of oxygen containing shielding gases. Due to absorption of oxygen in the liquid metal the surface tension will change. As a general rule oxidising components in the shielding gas will lead to a decrease of the surface tension, which results in improved wetting behaviour, enhanced penetration and an improved weld bead profile [C.2 -C.4]. However, an Ar-CO₂ shielding gas with a CO₂ content up to 10%, results in high wetting angles and the possibility of humping and undercutting [C.5, C.6].
Appendix C

Rimskii et al. [C.4] measured the oxygen concentration in droplet and weld metal in the case of open arc GMA welding of mild steel with several shielding gas compositions. They found that the oxygen concentration in the droplet and the weld pool increases considerably when CO₂ or O₂ is added to the shielding gas (by a factor of six when CO₂ is used instead of Ar). Some of the results are given in Table C.1. As expected, the oxygen content in the weld metal is slightly lower than that in the liquid droplet.

![Graph showing surface tension of liquid iron as a function of oxygen concentration.](image)

**Fig. C.1** Surface tension of liquid iron as function of the oxygen concentration [C.1].

<table>
<thead>
<tr>
<th>shielding gas</th>
<th>[O] -droplet (wt %)</th>
<th>[O]-weld metal (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>0.0101</td>
<td>0.0090</td>
</tr>
<tr>
<td>Ar-5% O₂</td>
<td>0.0149</td>
<td>0.0109</td>
</tr>
<tr>
<td>Ar+25% CO₂</td>
<td>0.0413</td>
<td>0.0403</td>
</tr>
<tr>
<td>Ar+5% O₂+25% CO₂</td>
<td>0.0421</td>
<td>0.0411</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.0648</td>
<td>0.0594</td>
</tr>
</tbody>
</table>
The influence of gases on the surface tension of liquid iron and low alloy steel was studied by Ershov et al. [C.7]. These authors found that the surface tension decreases with oxygen content in the liquid metal. A percentage of oxygen content comparable to the concentrations found by Rimskii et al. [C.4] during welding with pure carbon dioxide, resulted in a decrease of the surface tension from 1.8 N/m in the case of pure iron to 1.125 N/m, see Fig. C.2. Similar results were found for low alloy steel, although no quantitative values of surface tension were presented.

Fig. C.2  Surface tension of liquid iron at 1600 °C as function of ■ [H], ● [O], ○ [N] [C.7].

Hazlett [C.8] studied the effect of a number of compounds used in the manufacturing of welding electrodes on surface tension, arc stability and bead shape. These experiments were carried out in different gas atmospheres. In the case of He and Ar atmospheres the pendant drop method was used, whereas in the case of N₂ and CO₂ atmospheres (in view of the distortion of the droplets by the formation of gas bubbles) the collected droplet technique was used. The results obtained by Hazlett in the case of mild steel (chemical composition: 0.25% C; 1.0% Mn; 0.20% Si; 0.04% P; 0.015% S; 0.25% Cr) are listed in Table C.2.
Table C.2  Surface tension (mN/m) of mild steel in different gas atmospheres [C.8].

<table>
<thead>
<tr>
<th>gas atmosphere</th>
<th>He</th>
<th>Ar</th>
<th>N₂</th>
<th>CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>surface tension</td>
<td>961</td>
<td>956</td>
<td>740</td>
<td>944</td>
</tr>
</tbody>
</table>

The surface tension of liquid metals is also influenced by temperature. Figure C.3 shows this influence for Fe-O [C.1]. The temperature coefficient of surface tension (Δγ/ΔT) depends on the oxygen concentration. In the case of mild steel, the surface tension increases with temperature. As already mentioned in chapter 3, Meyendorf et al. [C.9, C.10] measured the droplet temperature and the weld pool temperature during short circuiting arc welding and found that a relation exists between both temperatures. The weld pool temperature is approximately 1550-1700 °C and is substantially lower than the droplet temperature.

When the voltage and/or the current are changed the temperature will change [C.11] and this will have consequences for the surface tension, see Fig. C.3.

No general agreement exists on the influence of the composition of the shielding gas and the arc plasma on the droplet temperature. In literature temperatures of the droplet near the boiling temperature are mentioned in the case of welding with inert shielding gases. When welds are made in multi-atomic gases, the temperature of the droplet does not reach the boiling temperature of the metal [C.11].

Lancaster [C.12] states that Ar - CO₂ arc temperature is relatively low and is hardly influenced by the CO₂ content. Van den Heuvel et al. [C.13] found that the temperature of the arc has only a small effect on the droplet temperature.
A number of experimental techniques is available to determine the surface tension of liquid metals. The most commonly used methods are: the drop shape method (sessile drop, pendant drop), the collected droplet technique and the maximum bubble pressure method [C.14].

In the sessile drop method the shape of a liquid drop resting freely on a horizontal surface is related to the surface tension and the gravitational force. The surface tension tends to draw the liquid into a sphere, whereas the gravity tends to flatten and spread the drop. In this method a direct contact exists between the liquid metal and a solid substrate. This experimental set-up provides a possible source of oxygen contamination of the liquid metal. The pendant drop method is similar to the sessile drop method in that the shape of the outline of the hanging drop is determined.

The collected droplet technique yields relatively low values of the surface tension because of the assumption that the neck, connecting the droplet to the rod, has the same diameter as the rod. The following expression is used for the calculation of the surface tension:

\[ \gamma = \frac{W_g}{2\pi r} \]  

(C.1)
with W the weight of the droplet, g the gravitational constant and r the radius of the rod. The maximum bubble pressure technique is based on forcing a gas through a capillary tube inserted in a melt. At a specific value of the gas pressure a bubble is formed at the end of the tube. This pressure is directly related to the surface tension of the liquid metal.

A quite different method of surface tension measurement is based on the speed of propagation of ripples across the surface of the liquid. The propagation speed of the ripples is dependent on the gravity and the surface tension according to the following equation:

\[ c = \sqrt{\frac{\lambda g + 2\pi\gamma}{2\pi + \frac{2\pi\gamma}{\rho\lambda}}} \]  \hspace{1cm} (C.2)

with c the propagation speed, \( \lambda \) the wavelength, g the gravitational constant, \( \gamma \) the surface tension and \( \rho \) the density of the liquid. In the case that the wavelength is small, the propagation speed of the wave is controlled by the surface tension, and the term containing the gravity force may be neglected [C.15].

Little information exists about the surface tension of liquid metals and alloys under arc welding conditions. Sahoo et al. [C.16] found that in the case of iron, the presence of a low pressure Ar plasma leads to a decrease in surface tension of approximately 0.1 N/m. Recently, Xiao et al. [C.17] determined the surface tension of liquid iron from the oscillation behaviour of the weld pool in the case of GTA welding and found values which lie in the same range as those obtained under non-arc conditions.

### C.2. Density of liquid metal

Like surface tension the density of the liquid metal is also influenced by the temperature [C.17]. The density can be expressed by the following equation:

\[ \rho = \rho_m \left(1 + \alpha(T - T_m)\right) \]  \hspace{1cm} (C.3)

with \( \rho \) the density of the liquid metal, \( \rho_m \) the density at the melting point, \( \alpha \) the density temperature coefficient, T the surface temperature of the weld pool and \( T_m \) the melting temperature of the metal.
In the case of short circuiting GMAW the variation in density due to changes in weld pool
temperature are limited and can be neglected.

C.3. Weld pool geometry

In chapter 2 the influence of the welding parameters on the weld bead dimensions are
discussed. With respect to the weld pool oscillation behaviour, the penetration profile plays an
important role. The assumptions used in modelling of weld pool oscillation (see Appendix B)
include a uniform depth of the pool and a small amplitude of the oscillation in comparison to
the wavelength. Under these conditions the pool bottom does not interfere with the oscillation
behaviour.

It appears that penetration depth is maximum when welding conditions are optimal, see Fig.
2.18. Furthermore, a finger shaped penetration profile is often observed during short circuiting
arc welding. Essers et al. [C.18, C.19] state that fingshape penetration in open arc welding is
caused by the momentum of droplets transferred to the weld pool and this is probably also the
case in short circuiting arc welding. Under extreme conditions lack of fusion (undercutting) can
be encountered near the weld pool boundary, especially under stubbing conditions and with
pure Ar gas shielding. This phenomenon conflicts with the assumption on which the equations
of weld pool oscillation are based. However, under optimal welding conditions lack of fusion
is not observed, although the geometry of the weld is not always perfect and a high wetting
angle is sometimes observed.

Another point of concern is the length to width ratio of the weld pool. Under stationary
conditions the weld pool (top view) is circular in shape. Increasing the travel speed results in
an elongated weld pool and the weld pool approaches an elliptical or tear drop shape. This
eventually leads to the occurrence of mode 2 oscillation [C.20]. However, in the present study
it was found that mode 2 oscillation does not occur when welding is carried out under optimal
welding conditions.

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A Study of Short Circuiting Arc Welding

Summary

Short circuiting gas metal arc welding is a very dynamic process, which is characterised by regular contact between the electrode wire and the workpiece. During this contact period, the arc is extinct and metal is transferred to the weld pool. The short circuit is ruptured under the action of gravity, surface tension and Lorentz forces after which the arc is immediately reignited. This cycle is repeated in a more or less regular way. The process can be followed by monitoring current and voltage as function of time. Current and voltage change in a cyclic way and this cyclic behaviour can be characterised by a number of process parameters, the most important being the arc time, the short circuit time and the short circuit frequency.

It appears that short circuiting arc welding is possible in a relatively large operating area, which is limited because:

• free flight transfer (detachment of discrete droplets from the electrode wire) occurs in the high voltage region,
• stubbing (electrode wire touches the bottom of the weld pool) takes place in the low voltage and high wire feed rate region,
• no weld pool is formed in the case of an extremely low heat input.

Within the short circuiting operating area, welding conditions and performance vary considerably. In the operating area a specific zone can be assigned where welding conditions are optimal, resulting in good weld bead appearance, low spatter and maximal depth of
Summary

penetration. The optimal conditions coincide with a minimum in arc time and a maximum in short circuit frequency.

An important aspect of short circuiting arc welding is the transport of heat, as it determines the electrode melting rate and the formation of the weld pool. Heat flow during short circuiting gas metal arc welding is governed by anodic arc heating of the electrode wire, cathodic arc heating of the workpiece and Joule heating of the electrode wire.

A model is derived which describes the heat transfer to the electrode and to the workpiece. Heat flow values predicted by the model are consistent with experimentally obtained data.

The efficiency of the heat transport can be described by the process efficiency and the melting efficiency.

Another interesting aspect is the mass transport from the electrode wire to the workpiece. This mass transport takes place during the short circuit period. The mass of liquid metal transferred during one short circuit cycle reaches a minimum for specific combinations of wire feed rate and voltage. Associated with metal transfer is the occurrence of spatter. Spatter is one of the main disadvantages of the short circuiting arc welding process. Experiments showed that spatter originates from the liquid bridge and is released as the bridge is ruptured. Spatter loss shows a minimum under the same conditions for which the transferred mass per short circuit is minimum and increases dramatically when stubbing occurs.

The stability of the short circuiting arc welding process can be described by the distributions of specific process parameters and/or the standard deviation of these parameters. Under stable welding conditions the distribution of the arc time and the short circuit frequency shows a single peak, whereas the standard deviations of these parameters reach a minimum.

This minimum corresponds to:

- optimal bead appearance,
- a maximum in depth of penetration,
- a minimum in arc time,
- a maximum in short circuit frequency,
- a maximum in melting efficiency,
- a minimum in mass transferred per short circuit,
- a minimum in spatter loss.

Based on this behaviour it is possible to assign a locus of optimal welding conditions in the voltage - wire feed rate diagram, where the process stability is maximum. It should be realised that the position of this locus shifts when the welding parameters are changed.

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The existence of a locus of maximum process stability can be explained on the basis of the occurrence of weld pool oscillations. Weld pool oscillations are triggered by the reignition of the arc after the rupture of the liquid bridge and by the momentum of liquid metal transferred. It appears that in the case of partial penetration the weld pool oscillates in a mode (surface oscillation) which differs from that in the case of full penetration (volume oscillation). In both cases the oscillation frequency is influenced by the physical properties of the liquid metal (surface tension and density) and by the dimensions of the weld pool.

In the case of partial penetration optimal welding conditions and maximum process stability occur when the oscillation frequency and the short circuit frequency are equal. During each oscillation of the weld pool contact is established between the weld pool surface and the pendant droplet.

In the case of gas tungsten arc welding an oscillation mode switch is observed, accompanied by a sharp decrease in the frequency, when partial penetration transfers to full penetration. It appears that this change in weld pool oscillation frequency does not take place in the case of gas metal arc welding, as burn-through will occur prematurely.

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March 4th
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Een onderzoek op het gebied van kortsluitboogglazen

Samenvatting

Kortsluitboogglazen is een zeer dynamisch lasproces, dat gekarakteriseerd wordt door een regelmatig contact tussen de elektrodedraad en het werkstuk. Tijdens deze contactperiode vindt het metaaltransport van de elektrode naar het lasbad plaats. De kortsluitperiode wordt afgesloten met het verbreken van de kortsluiting (vloeistofbrug) waarna de elektrische boog herontsteekt. De cyclus herhaalt zich met een zekere regelmaat.

Tijdens het lassen varieert de spanning en de stroomsterkte tussen het kortsluitniveau en het boogniveau. De registratie van de spanning en de stroomsterkte als functie van de tijd maakt het mogelijk het proces te beschrijven in termen van boogtijd, kortsluittijd en kortsluitfrequentie.

Het blijkt dat kortsluitboogglazen mogelijk is binnen een relatief groot spanning - stroomsterkte gebied. Dit gebied wordt echter begrensd door:
• het open-booglassen bij relatief hoge waarden van de spanning; het materiaaltransport vindt plaats in de vorm van discrete druppels,
• het stoten van de elektrodedraad op de bodem van het lasbad (stubbing); stoten geschiedt bij een lage spanning en een hoge draadaanvoersnelheid,
• het uitblijven van de vorming van het lasbad door een extreem lage warmte-inbreng.

Binnen het relatief grote gebied waar kortsluitboogglazen mogelijk is varieren de lasomstandigheden aanzienlijk. Er kan in dit gebied echter een specifieke zone worden
aangegeven waarbinnen de lascondities optimaal zijn. Lassen onder deze omstandigheden resulteren in een goed lasuitertrekje, weinig spatten en een maximale inbrandingsdiepte.

Een belangrijk aspect bij het kortsluitbooglassen is het warmtetransport. Het warmtetransport bepaalt de neersmelt snelheid van de elektrodedraad en de vorming van het lasbad. De belangrijkste warmtebronnen zijn de anodische verwarming van de elektrodedraad, de kathodische verwarming van het werkstuk en de weerstandsverhitting (Joule verhitting) van de elektrodedraad.

De warmtestromen van het proces kunnen worden beschreven met een model waarin deze warmtebronnen zijn verwerkt. De berekende waarden uit het model komen goed overeen met de experimenteel, door middel van calorimetrische experimenten, bepaalde waarden. De efficiëntie waarmee het warmtetransport plaatsvindt kan worden uitgedrukt in het procesrendement en het smeltrendement.

Een ander belangwekkend aspect van het kortsluitbooglassen is het materiaaltransport van de elektrode naar het werkstuk. Het materiaaltransport geschiedt tijdens de kortsluitperiode. Aan het einde van de kortsluitperiode wordt de vloeistofbrug tussen de elektrodedraad en het lasbad onder invloed van een aantal krachten verbroken en ontsteekt de boog. De per kortsluiting getransporteerde massa vertoont een minimum voor specifieke waarden van stroom en spanning. Een ongewenst verschijnsel dat direct gelieerd is met het metaaltransport is het optreden van spatten. Uit experimenten blijkt dat spatten hun oorsprong vinden in de vloeistofbrug en vrijkomen als de brug wordt verbroken. Het spatverlies vertoont een minimum onder dezelfde lasomstandigheden als waaronder een minimum in de getransporteerde massa per kortsluiting wordt waargenomen en neemt dramatisch toe wanneer stoten van de elektrodedraad in het lasbad beginnende op te treden.

De stabiliteit van het kortsluitbooglasproces kan worden beschreven door middel van de verdeling van specifieke lasparameters en/of de standaarddeviatie in deze parameters.

Onder stabiele lasomstandigheden vertoont de verdeling van de kortsluitstijd, de boogtijd en de kortsluitt frequentie één piek terwijl de standaarddeviaties van deze parameters minimaal zijn. Deze minima corresponderen met:

- een optimaal lasuitertrekje,
- een maximale penetratiediepte,
- een minimale boogtijd,
- een maximale kortsluitfrequentie,
- een maximum in het smeltrendement.
Samenvatting

- een minimum in de massa getransporteerd per kortsluiting,
- een minimaal spatverlies.

Op basis van dit gedrag kan in het spanning - draadsnelheiddiagram een smalle zone met optimale lasparameters worden aangegeven, waarin de stabilititeit van het proces maximaal is. Een verklaring voor het optreden van deze zone kan worden gegeven op basis van de aanwezigheid van oscillaties in het lasbad.

Lasbadoscillaties worden opgewekt door de boogdruk die optreedt bij de herontsteking van de lasboog nadat de vloeistofbrug verbroken is en door de impuls van de getransporteerde massa. Het blijkt dat het lasbad bij het geval van onvolledige doorlassing in een andere mode (oppervlakte oscillatie) oscilleert dan in het geval van volledige doorlassing (volume oscillatie). In beide gevallen wordt de oscillatiefrequentie beïnvloed door de fysische eigenschappen van het vloeibare metaal (in het bijzonder de oppervlaktespanning en de dichtheid) en de afmetingen van het lasbad.

Bij onvolledige doorlassing trekken optimale lasomstandigheden en een maximale processtabiliteit op indien de oscillatiefrequentie van het lasbad overeenkomt met de kortsluitfrequentie. Onder deze omstandigheden maakt het lasbad tijdens elke oscillatie van het lasbad contact met de aan de elektrodedraad hangende druppel.

Bij het TIG (GTA) lassen wordt een verandering van oscillatiemode waargenomen die vergezeld gaat met een sterke reductie in de frequentie, wanneer onvolledige lasbadpenetratie overgaat in volledige penetratie. Uit dit onderzoek blijkt dat deze frequentiesprong niet optreedt bij het MIG/MAG (GMA) lassen omdat hierbij reeds in een eerder stadium doorbranden van het lasbad zal optreden.

Delft, Nederland,
4 maart 1997.
M.J.M. Hermans
Eine Studie bezüglich des Kurzschlußlichtbogenschweißprozesses

Zusammenfassung


Es stellt sich heraus, daß Kurzschlußlichtbogenschweißen möglich ist innerhalb eines relativ großen Spannung-Stromstärke-Bereiches. Dieser Bereich wird jedoch begrenzt durch:
• das offene Lichtbogenschweißen, bei relativ hohen Spannungswerten; der Materialtransport findet statt in Form diskreter Tropfen,
• das Anstoßen des Elektrodendrahts an den Schweißbadboden (Stubbing); das anstoßen findet statt bei geringer Spannung und einer hohen Drahtvorschubgeschwindigkeit,
• das Ausbleiben der Schweißbadbildung durch extrem niedriger Wärmeeinleitung.

Innerhalb des relativ großen Bereiches, in dem Kurzschlußlichtbogenschweißen möglich ist, unterscheiden sich die Schweißumstände wesentlich. Es kann jedoch innerhalb dieses Bereiches ein spezifisches Gebiet angegeben werden, innerhalb dessen die Schweißbedingungen optimal sind. Schweißen unter diesen Umständen ergibt ein gutes äußeres Schweißbild, weniger Spritzer sowie eine maximale Einbrandtiefe.

Ein wichtiger Aspekt beim Kurzschlußlichtbogenschweißen ist der Wärmeverlusttransport. Dieser Wärmeverlusttransport bestimmt die Abschmelzgeschwindigkeit des Elektrodendrahts sowie die
Zusammenfassung

Bildung des Schweißbads. Die wichtigsten Energiequellen sind die anodische Lichtbogenergie, die kathodische Lichtbogenergie und die Widerstandserhitzung (Joulsche Erhitzung) des Elektrodendrahts.


Die Stabilität des Kurzschlußlichtbogenschweißprozesses kann angegeben werden mittels der Verteilung spezifischer Schweißparameter und/oder der Standardabweichung in diesen Parametern. Unter stabilen Schweißumständen weist die Verteilung der Kurzschlußzeit, der Lichtbogenzeit sowie der Kurzschlußfrequenz einen Spitzenwert auf, während die Standardabweichungen dieser Parameter minimal sind. Diese Mindestwerte stimmen überein mit:

- einen optimalen äußeren Schweißbild,
- einer maximalen Durchdringungstiefe,
- einer minimalen Lichtbogenzeit,
- einer maximalen Kurzschlußfrequenz,
- einem Maximum an Schmelzwirkungsgrad,
- einem Minimum an Masse, pro Kurzschluß transportiert,
- einem minimalen Spritzverlust.
Aufgrund des vorhergehenden ist es möglich, einen schmalen Bereich mit optimalen Schweißparametern anzugeben. In diesem Bereich ist die Stabilität des Prozesses maximal. Die Position dieses Optimalbereiches verschiebt sich, wenn sich die Schweißbedingungen ändern.

Es ist möglich, die Existenz eines Bereiches maximaler Prozeßstabilität zu erklären aufgrund vorhandener Oszillationen im Schweißbad.
Schweißbadoszillationen werden hervorgerufen durch den Lichtbogendruck der auftritt beim erneuten Zünden des Schweißlichtbogens, nachdem die Flüssigkeitsbrücke unterbrochen ist, sowie durch den Impuls der transportierten Masse.
Es zeichnt sich, daß das Schweißbad infolge unvollständigen Durchschweißens in einen anderen Modus (Oberflächenoszillation) oszilliert, als im Falle vollständigen Durchschweißens (Volumenoszillation). In beiden Fällen wird die Oszillationsfrequenz beeinflußt von den physischen Eigenschaften des flüssigen Metalls (im Besonderen die Oberflächenspannung sowie die Dichte) und von den Abmessungen des Schweißbades. Bei unvollständigen Durchschweißen treten optimale Schweißumstände sowie eine maximale Prozeßstabilität auf, wenn die Oszillationsfrequenz im Schweißbad übereinstimmt mit der Kurzschlußfrequenz. Unter diesen Umständen hat das Schweißbad während jeder Oszillation dieses Schweißbades Kontakt mit dem am Elektrodendraht hängenden Tropfen.
Beim TIG (GTA) - Schweifen wird eine Veränderung des Oszillationsmodus festgestellt, die einhergeht mit einer starken Reduzierung in der Frequenz, wenn eine Teildurchdringung des Schweißbades übergeht in eine vollständige Durchdringung. Aus dieser Untersuchung geht hervor, daß dieser Frequenzsprung nicht auftritt beim MIG/MAG (GMA) - Schweifen, weil hier schon zu einem früheren Zeitpunkt ein Durchbrennen des Schweißbades auftreten wird.

Delft, Niederlande,
M.J.M. Hermans
Une Etude du Procédé de Soudage Electrique en Court-Circuit

Resumé

Le soudage électrique en court-circuit est un procédé de soudage très dynamique, étant caractérisé par le contact régulier entre l’électrode et la pièce à souder. Pendant cette période de contact a lieu le transport du métal de l’électrode au bain de soudage. Cette période de court-circuit se termine par la rupture du court-circuit (le pont-liquide), après cette rupture l’arc électrique se rallumera. Le cycle se répète assez régulièrement.

Il se trouve que le soudage électrique en court-circuit est réalisable dans une zone de tension et d’intensité du courant relativement grande. Seulement cette zone est limitée par:
• le soudage à arc ouvert, si les valeurs de tension sont relativement élevées; le transport du matériel se fait sous forme de gouttes discrètes,
• quand l’électrode bute sur le bain de soudage (stubbing); l’action de buter se fait sous une tension basse et un transport très rapide d'électrode,
• le manque d'un bain de soudage par un apport de chaleur extrêmement bas.

Dans la zone relativement grande où le soudage électrique en court-circuit est possible, les conditions de soudage sont très variées. Pourtant, dans cette zone on peut indiquer un domaine spécifique où les conditions de soudage sont optimales. Le soudage sous ces circonstances résulte dans un bon aspect extérieur, peu d'éclats et une profondeur de soudage maximale.

Un aspect important du soudage électrique en court-circuit est le transport de la chaleur. Celle-ci détermine la rapidité de la fonte de l’électrode et la formation du bain de soudage. Les
sources d'énergie sont l'énergie de l'arc anodique et de l'arc cathodique ainsi que le réchauffement par résistance de l'électrode (le réchauffement de Joule).

Ces sources d'énergie peuvent être incorporées dans un modèle décrivant les courants de chaleur du procédé.

Les valeur calculées du modèle correspondent bien avec les valeurs déterminées à l'aide d'expérimentations calorimétriques. L'efficacité du transport de la chaleur peut être décrite à l'aide du rendement du procédé et celui de la fonte.

Un autre aspect important du soudage électrique en court-circuit est le transport du matériel de l'électrode à la pièce à souder. Le transport se fait dans la période du court-circuit. A la fin de cette période le pont liquide entre l'électrode et le bain de soudage est rompu sous l'influence de plusieurs forces et l'arc s'allume. La masse transportée par période de court-circuit montre un minimum de valeurs spécifiques de courant électrique et de tension. Un phénomène désagréable directement lié au transport de métal est l'apparition des éclats. Les expérimentations montrent que l'origine des éclats se trouve dans le pont liquide et qu'ils se forment, quand le pont est rompu. La perte par les éclats montre un minimum sous les mêmes circonstances de soudage quand on observe un minimum dans la masse transportée par court-circuit et elle augmente d'une façon dramatique, quand l'électrode commence à buter dans le bain de soudage.

La stabilité du procédé de soudage en court-circuit peut être décrite à l'aide d'une répartition de paramètres de soudage spécifiques et/ou la déviation standard dans ces paramètres. Sous des circonstances de soudage stables la répartition de la période du court-circuit, le temps de l'arc et la fréquence du court-circuit montrent un sommet, tandis que déviation standard de ces paramètres sont minimes. Ce minima correspondent avec:

- un aspect extérieur de la soudure optimal,
- une profondeur de pénétration maximale,
- une période d'arc minime,
- une fréquence de court-circuit maximale,
- un maximum de rendement de fonte,
- une perte par éclats minime.

Etant donnés les faits mentionnés ci-dessus on peut indiquer une zone très étroite avec des paramètres de soudage optimaux. Dans cette zone la stabilité du procédé est optimale. La position de cette zone se déplace quand on varie les conditions de soudage.
Résumé

On peut expliquer cette zone de stabilité du procédé maximale par l'existence d'oscillations dans le bain de soudage. Ces oscillations naissent par la pression de l'arc quand il se rallume, après que le pont liquide a été rompu par l'impulsion de la masse transportée. Il se trouve qu'en cas de soudage complet, le bain de soudage oscille dans un autre mode (oscillation de surface) qu'en cas de soudage complet (oscillation de volume). Dans les deux cas la fréquence d'oscillation est influencée les caractéristiques physiques du métal liquide (en particulier la tension de surface et la densité) et les dimensions du bain de soudage.

Un soudage incomplet produit des circonstances de soudage optimales et une stabilité du procédé maximale, si la fréquence du bain de soudage correspond à la fréquence du court-circuit. Sous ces circonstances le bain de soudage prend contact avec la goutte qui pend à l'électrode lors de chaque oscillation du bain.

Le soudage TIG (GTA) montre un changement du mode d'oscillation accompagné d'une forte réduction de la fréquence, quand la pénétration partielle du bain de soudage change en pénétration complète. Cette étude montre que ce saut de fréquence ne se présente pas dans le soudage MIG/MAG (GMA), parce que le bain de soudage sera percé plus tôt.

Delft, Pays-Bas,
le quatre Mars, 1997,
M.J.M. Hermans
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