stellingen

behorende bij het proefschrift

weld pool oscillation for penetration sensing and control

door Ton Aendenroomer,
Delft, 20 februari 1996

1. Tijdens het lassen zijn er in het lasbad verschillende oscillatiemodes mogelijk. Deze oscillatiemodes kunnen, afhankelijk van de doorlassingssituatie, zowel afzonderlijk als in combinatie optreden.

dit proefschrift

2. De door Zhang et al. voorgestelde, op lasbadinzakking gebaseerde, sensor is alleen geschikt voor het detecteren van overmatige doorlassing.

3. Toepassing van de resonantiemethode van Wang et al. gaat voorbij aan het probleem van de onvoorspelbaarheid van de lasbadgrootte in praktijksituaties en heeft bovendien een onacceptabel lasuiters tot gevolg.

4. Het feit dat het plasmalassen slechts een marginaal aandeel inneemt als industrieel lasproces is op zowel technische als economische gronden onverklaarbaar.

5. De huidige trend van toenemende produktaansprakelijkheid door fabrikanten zal tot gevolg hebben dat in de laspraktijk eindelijk meer aandacht op de kwaliteit en minder op de produktiviteit wordt gevestigd.

6. Men kan pas met recht van succesvolle spraakherkenning spreken als computers het commando "schiet eens op" ook daadwerkelijk uitvoeren.

7. Om burenruzie te vermijden dient men klassieke muziek thuis slechts te beluisteren met de afstandsbediening binnen handbereik.
8. De universitaire wachtgeldregeling is een praktijkvoorbeeld van positieve terugkoppeling: om de wachtgelden te kunnen betalen zullen de universiteiten nog meer mensen moeten ontslaan.

9. “Just-in-time” voorraadbeheer levert in de meeste gevallen slechts een marginale kostenbesparing op en is bovendien slecht voor het milieu.

10. Als de voorschriften t.a.v. experimenteren buiten de reguliere werktijden strikt zouden worden nageleefd, zou het percentage AI0’s dat binnen 4 jaar promoveert nog lager uitvallen dan de huidige 7 %.

11. Indien men de kosten van ontmanteling meerekent, kan de kWh prijs van kernenergie niet concurreren met die van windenergie.

12. De recente waarnemingen waaruit blijkt dat de leeftijd van het heelal korter is dan de leeftijd van de oudste sterren kunnen verklaard worden met een variabele lichtsnelheid.
weld pool oscillation for penetration sensing and control
weld pool oscillation for penetration sensing and control

proefschrift

ter verkrijging van de graad van doctor aan de Technische Universiteit Delft
op gezag van de Rector Magnificus Prof. ir. K.F. Wakker,
in het openbaar te verdedigen ten overstaan van een commissie,
door het College van Dekanen aangewezen,
op dinsdag 20 februari 1996 te 16.00 uur

door

Antonius Johannes Rosa AENDENROOMER

natuurkundig ingenieur,
geboren te Hunsel
Dit proefschrift is goedgekeurd door de promotor

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chapter 1

General introduction

Electric arc welding is one of the major processes for joining metals in industrial applications. These applications range from joints in thin sheets less than half a millimeter thick to joints in centimeters thick material with a gap of several millimeters. Undoubtedly, this wide range of applications involves completely different variants of the same arc welding process, such as shielded metal arc welding (SMAW), gas metal arc welding (GMAW), submerged arc welding (SAW) and gas tungsten arc welding (GTAW).

A specific feature and an important advantage of the arc welding process is the fact that high energy density can be generated by means of relatively simple equipment (in comparison with for example laser welding or electron beam welding).

The heat source used in electric arc welding is the arc plasma, which typically has an axial temperature in the range of 5000 to 15000 K. This temperature is determined by the equilibrium which exists between the various particles present in the arc plasma, when the electric current exceeds a certain level (about 10 A under normal conditions; by manipulating the arc environment this level can be reduced). The arc plasma is electrically neutral except in the extremely thin regions near the anode and cathode. These regions are governed by negative and positive space charge, respectively.
General introduction

An electric arc burns in an ionized gas between two electrodes: the cathode and the anode. In Fig. 1.1 the situation is depicted which occurs when the electrodes are cylindrical in shape and are placed horizontally at relatively large distance from each other. The typical arc shape which can be observed under these conditions is a consequence of the low specific mass of the plasma gas due to its high temperature, as a result of which it will tend to rise.

![Diagram of arc shape](image)

**Fig. 1.1** Arc shape in the case of horizontal (identical) electrodes (a) and arc (bell) shape in real welding situation (b).

In the case of arc welding one of these electrodes (either the cathode or the anode) serves as the workpiece; the remaining electrode is simply called “electrode” and is fitted in the welding torch, connected to the power supply. Under realistic welding conditions the workpiece is non-cylindrical (locally flat) and the distance between electrode and workpiece is relatively small (a few mm). As a consequence of this, the arc becomes bell shaped (see Fig. 1.1b): narrow at the electrode and wide at the workpiece. In the center of the arc the temperature can become as high as 15000 K; however, near the electrodes the
temperature will be considerably lower. As an illustration of the temperature distribution in the arc, the isothermals in a 5 mm argon arc are plotted in Fig. 1.2.

Heat transport from the arc to the anode and cathode takes place by means of radiation, conduction and convection. Furthermore, at the anode there is a positive contribution of the electron work function and of the electron heating effect (cooling down of the electrons from arc temperature to anode temperature); at the cathode this contribution is negative. Consequently, the anode is the “hot” electrode and the cathode the “cool” electrode under normal welding conditions. Normally, the heat input is sufficiently large to melt a substantial part of the material and the formation of a weld pool of liquid metal is the result. The weld pool extends over both sides of the seam and penetrates to a certain depth. After solidification of the liquid metal the two parts of the workpiece are joined and form one structure. During welding the arc moves along the seam, melting new material ahead and leaving solidified material behind, which results in a permanent joint.

Fig. 1.2 Isothermals in a 200 A argon arc of 5 mm length between a tungsten electrode and a water cooled copper anode [1.1].
General introduction

Arc welding is particularly suited to achieve high melting rates when a fusible electrode is used in the form of a wire, a strip or a rod. In these cases the following process variants can be distinguished (Table 1.1):

<table>
<thead>
<tr>
<th>process</th>
<th>electrode</th>
<th>shielding</th>
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<td>SMAW</td>
<td>shielded metal arc welding</td>
<td>solid rod with coating</td>
</tr>
<tr>
<td>GMAW</td>
<td>gas metal arc welding</td>
<td>solid or flux-cored wire</td>
</tr>
<tr>
<td>SAW</td>
<td>submerged arc welding</td>
<td>solid or flux-cored wire, strip</td>
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Shielding is necessary to protect the liquid metal from oxidizing. This can be done by means of a gas flow (GMAW) or by slag formation (SMAW and SAW). Often the electrode contains reducing elements to decrease the oxygen content of the liquid.

When not the melting rate but the quality of the joint is the most important factor, a non-fusible tungsten based electrode is used instead of a fusible electrode. This process is called gas tungsten arc (GTA) welding. Fusible material can be added by means of an extra rod or wire or by means of fusible inserts to fill the seam gap. Normally, GTA welding is carried out with direct current, electrode negative. In the case of aluminum alloys, welding is carried out with alternating current.

Since its introduction, the GTA welding process has been the logical choice in many critical welding situations, like thin sheet welding or root pass welding for high pressure applications. The materials which have successfully been welded with the GTAW process include high alloy steels like austenitic steels or duplex steel and non-ferro materials like titanium and copper-nickel alloys.

An important step forward in the field of high quality welding was the introduction of pulsed current GTA welding in the late 60's. The pulsed current welding sources which have been introduced on the market were first thyristor controlled, later transistor controlled for pulse frequencies up to 1000 Hz. After introduction of microprocessors, the primary circuit switched mode power sources (inverter types) entered the market, as a consequence of which the prices dropped considerably.
The pulsed GTA welding process makes a fine control of the heat input possible, a practice being used by manual welders for years by means of moving the torch stepwise along the seam. The pulsed GTAW process proved its importance in out-of-position welding and orbital tube welding, the two challenges in today's welding practice, and is nowadays the logical choice for these applications.

Out-of-position welding (welding in the non-flat position) and orbital tube welding (welding in the orbital direction around a pipe or tube; orbital welding is actually a special form of out-of-position welding) are of specific interest in the metal fabrication industry. In this industry welding of pipe and tubular structures forms a substantial part of the welding activity, especially in the construction of power plant, chemical and petrochemical plant, oil refinery, food industry, aeronautic and space industry, as well as in construction of on- and off-shore pipelines. Without exception these structures are exposed during their lifetime to extreme physical or chemical actions due to high pressure or highly corrosive surroundings.

It is difficult to manipulate these structures to a comfortable (flat) position for welding. Although there are so-called manipulators on the market which can rotate (manipulate) tubular structures of several tons during welding, so that the welding torch can remain in the vertical position, most of these construction sites obstruct the possibility of manipulation because of their large dimensions. For example, one pipeline element can be manipulated, but 1000 km of pipeline ask for other solutions.

With the pulsed GTA welding process and a variety of orbital tube welding torches, a dedicated set of tools have come into the hands of the welding engineer, making it possible to tackle a substantial part of the orbital welding problems [1.2-1.6]. Although computer control is incorporated in most of today's top-of-the-market power supplies and welding heads (like programmable pulse patterns for different segments, (pulsed) wire supply control, lateral weave control and arc length control), sensing and control of the welding process is still in the hands (and eyes) of the operator.

One of the most important problems in today's state-of-the-art welding is sensing and control of weld penetration. Many attempts have been made throughout the years in developing sensing devices for weld penetration, but none of them has proven to be successful in production circumstances.
General introduction

The aim of this thesis is to study the possibilities and limitations of a new penetration sensing concept, based on weld pool oscillation. The advantage of this approach is that sensing occurs through-the-arc, making additional sensor heads superfluous. Pioneering work on this sensor concept has been carried out by Xiao [1.7]. This thesis focuses on incorporating the (theoretical) sensor concept into a prototype of an "intelligent" power source. This should result in a welding set-up with feedback equipment for in-process quality maintenance, its functionality being proven by systematic experiments on laboratory scale.

In chapter 2 of this thesis the physical background of the various penetration problems are discussed, after which an overview of the different sensor concepts, developed so far, is given in chapter 3. The principle of weld pool oscillation is discussed in chapter 4 and the applications of this principle on the standard process for pulsed GTA welding, are outlined in chapter 5, resulting in a concept of a penetration sensor which can sense the difference between underpenetration, correct penetration and overpenetration. This sensor principle is extended for the problems, caused by deviations as a consequence of positional welding and welding with cold wire supply which is treated in chapter 6 and chapter 7, respectively. The algorithm of an in-process penetration control (IPPC) system based on this principle, together with an alternative approach (spot welding), is described in chapter 8 and the feasibility of IPPC is demonstrated in chapter 9.
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chapter 2

Heat flow during welding

2.1 Introduction

A common feature of all arc welding processes is that a weld pool is formed which extends over either side of the seam that separates the two parts of the workpiece. Upon solidification of the liquid metal in the pool this results in a weld bead. One of the most important factors that determines the quality of the weld is the degree of penetration, which can be defined as the relative pool depth, compared to the thickness of the workpiece. For high quality welds the penetration depth must be equal to the thickness of the workpiece. Figure 2.1 shows a cross section of a weld which does not penetrate to the underside of the material (Fig. 2.1a) and a weld which does penetrate to the underside (Fig. 2.1b). In Fig. 2.1a only the upper part of the two materials is joined by the weld, leaving a gap at the underside and therefore introducing a weakness in the structure. The distinctive situations in Figs. 2.1a and 2.1b are called partial penetration and full penetration, respectively. It is evident that full penetration is demanded in high quality welds. There are specific situations where this can be achieved by means of a sealing weld (Fig. 2.1c): a second weld run is made at the underside of the workpiece with a slightly lower heat input than applied in the first run. However, not all situations allow such a strategy: the underside must be accessible for the welding torch.
Heat flow during welding

Since full penetration of the weld pool is demanded in high quality welds, the pool depth is the most important geometric parameter of the weld pool. In some welding processes, like electron beam welding or laser welding, the pool width can also be critical, but in arc welding this situation is rarely encountered. A narrow and deep weld pool is therefore preferred over a wide and shallow weld pool. In addition to the efforts to increase the total amount of molten material, it is also possible to influence the shape of the weld pool with the same amount of molten material by increasing the depth and decreasing the width.

Fig. 2.1 Different penetration situations: a) partial penetration, b) full penetration and c) partial penetration with sealing weld.
2.2 The weld pool geometry

According to physical laws, the size (or mass) of the weld pool is determined by the heat balance. The amount of molten metal which is produced per unit time can only be increased by increasing the heat input and/or by decreasing the heat output. The heat input is determined by the process conditions (welding current, travel speed, arc length, shape of the arc, shielding gas, electrode polarity, electrode top angle), the heat output by the properties of the workpiece (physical properties of the material, geometry, seam preparation, positioning, preheating). The heat input $Q$, defined as the amount of energy transferred to the workpiece per unit length, can be expressed as:

$$Q = \frac{\eta VI}{v}$$

(2.1)

with $V$ the arc voltage, $I$ the arc current, $v$ the travel speed and $\eta$ the process efficiency, defined by:

$$\eta = \frac{\text{energy transferred to the workpiece}}{\text{energy generated by the heat source}}$$

(2.2)

For GTA welding with the electrode negative $\eta = 0.5 - 0.8$. The geometry of the weld pool, which is defined as the shape of the pool at a given weld pool mass, is determined by the heat conduction of the material and the liquid motion (convection) in the weld pool, the latter playing a dominant role as will be explained in the next two sections.
2.3 Heat conduction

A convenient way to describe the processes which determine the size (or mass) of the weld pool is to consider the heat balance:

\[ \rho c \frac{\partial T}{\partial t} = \nabla[k \nabla T] - \rho cv \nabla T + q \]  

(2.3)

in which \( \rho, c, k, v, q, T \) and \( t \) are the specific mass, specific heat, heat conductivity, travel speed, heat production per unit volume per unit time, temperature and time, respectively.

The left hand side of equation (2.3) represents the temperature change in a volume element per unit time. The first term on the right hand side represents the temperature change due to heat conduction, the second term the temperature change due to motion (the change of the relative distance between the heat source and the volume element under consideration). The last term represents the heat production in the specific volume element per unit time; this is the arc heating when the volume element lies just underneath the arc. If the volume element lies at the front of the weld pool, then \( q \) represents the (negative) melting heat; if the volume element lies at the back of the weld pool, then \( q \) represents the (positive) solidification heat. In an attempt to solve equation (2.3) moving coordinates are applied (\( \partial T/\partial t = 0 \)) and the following simplifications are introduced (the Rosenthal solution [2.1]):

- the (arc) heat source is a point source and has an infinitely high temperature;
- the physical properties of the material are independent of temperature;
- there is no heat exchange between workpiece and surroundings;
- the workpiece is flat and is infinitely large;
- no melting and solidification occurs.

In [2.2] the solution of equation (2.3) under these simplifications is given for both a 2-dimensional and a 3-dimensional situation, resulting in the following equations for the temperature in a 2-dimensional and a 3-dimensional situation, respectively:

\[ 2D \quad T(t,r) - T_0 = \frac{Q}{2dk} \sqrt{\frac{\alpha}{\pi t}} \exp\left(-\frac{r^2}{4\alpha t}\right) \]  

(2.4a)
Heat flow during welding

\[ T(t,r) - T_0 = \frac{Q}{2\pi k t} \exp\left(-\frac{r^2}{4\alpha t}\right) \]

(2.4b)

in which \( d \) is the thickness of the workpiece, \( \alpha = k/cp \) the thermal diffusivity, \( r \) the distance from the heat source and \( T_0 \) the temperature of the workpiece before welding.

Equations (2.4a) and (2.4b) show that the temperature increase at a specific point is proportional with \( 1/\sqrt{t} \) for the 2-dimensional situation and with \( 1/t \) for the 3-dimensional situation (except for very small \( t \)), resulting in a much larger weld pool and heat-affected zone in the 2-dimensional situation than in the 3-dimensional situation.

In practical circumstances the 2-dimensional situation can be used as an approximation for single pass welding in an I-groove and the 3-dimensional situation for root pass welding in a V-groove.

2.4 Convection

Although several attempts have been made to modify the Rosenthal model, for instance by replacing the point heat source by a more realistic Gaussian heat distribution \([2.2]\), researchers have come to the conclusion that even the most detailed models based on heat conduction can not explain the large differences in penetration depth, often observed in different charges of the same material (so-called cast-to-cast variations).

This section focuses on the mechanism of convection in the weld pool. Convection is an important factor in the heat transport sequence during welding: it influences the direction of the heat flow in the liquid metal and determines whether a weld pool is narrow and deep or wide and shallow.

A weld pool can be considered as a dynamic fluid system, influenced by internal and external forces, causing specific types of fluid motion. Besides weld pool oscillations which are dealt with in chapter 4, the fluid motion in the weld pool appears as a so-called toroidal flow. This rotational flow has two basic appearances: outward (type A) or inward (type B) directed, respectively.
Heat flow during welding

Type A flow is radially outward along the surface, downward at the edges of the weld pool and upward in the middle; type B flow is inward along the surface, downward in the middle and upward at the edges of the pool (see Fig. 2.2). As can be seen in this figure, the direction of fluid flow strongly influences the shape of the weld pool: due to the transport of the arc heat from the middle of the pool an outward flow causes a wide and shallow weld pool, whereas an inward flow leads to a narrow and deep weld pool. The flow pattern also influences other aspects of the weld quality, like grain size, macro-segregation, porosity and the occurrence of undercutting [2.4, 2.5]. Furthermore, it appears that a more stable arc is established when the flow is inward directed [2.6].

![Diagram of weld pool flow](image)

Fig. 2.2 Top view and cross section of weld pool with convection flow, a: A-type (outward) convection flow and b: B-type (inward) convection flow.

There are several forces which act on the liquid in a weld pool and can drive the liquid in a toroidal convection flow: electro-magnetic forces, forces caused by variations in surface tension, forces caused by variations in specific mass and forces due to the plasma jet.
Heat flow during welding

**Electro-magnetic forces**

Due to the divergence of the electric current in the weld pool, electro-magnetic forces (Lorentz forces) act on the liquid metal in the weld pool.

The Lorentz force $\mathbf{F}_L$ is dependent on the current density $\mathbf{J}$ and the magnetic field $\mathbf{B}$:

$$\mathbf{F}_L = \mathbf{J} \times \mathbf{B}$$

and causes an upward force on the liquid weld metal at the edge of the weld pool (under the assumption that the current flow is radially outward directed) and therefore results in a type B flow in the weld pool.

In situations where the workpiece is not symmetrically connected with the mass of the power source, the current flow runs merely in one direction of the weld pool, causing the Lorentz force to act only on one side of the weld pool. Consequently, there is a rotational flow, upward at one side and downward at the other side of the weld pool, resulting in an asymmetric pool shape.

An application of electro-magnetic forces for stirring the weld pool has been reported back in 1953 by Patriarca and Slaughter [2.7]. They showed that it is possible to use the electro-magnetic stirring effect to improve the metallurgical structure like grain refinement, to reduce porosity, to improve the weld bead structure like depth-to-width (d/w) ratio or to improve the fusion when welding two dissimilar metals [2.8]. Nowadays electro-magnetic stirring is used on a relatively wide scale for specific applications.

**Variations in surface tension**

Variations in surface tension are caused by variations in temperature in the weld pool, which is maximum in the middle (under the arc) and minimum at the edges (melting point of the material).

The sign of the surface tension gradient $\partial \gamma / \partial T$ determines whether the surface tension force acts in the same or in the opposite direction of the temperature gradient. For a pure metal, $\partial \gamma / \partial T$ is negative and the resulting flow (Marangoni flow) is of type A. Some alloying elements and impurities, in particular the elements sulphur, selenium and oxygen (surface active elements) are responsible for an increase in surface tension with increasing
Heat flow during welding

temperature. Actually, these elements decrease the surface tension at the melting temperature and their effectiveness becomes less pronounced at higher temperature (see Fig. 2.3). Consequently, the Marangoni flow is of type B [2.10]. Decreasing the amount of surface active additives causes the Marangoni flow to turn from type B to type A, as a consequence of which the weld pool shape turns from narrow and deep to wide and shallow. Research on the effects of surface active elements by Heiple et al. [2.6, 2.9-2.11] has shown that even very small additions of these elements can cause a dramatic increase in d/w ratio. For instance, an increase of 160 % in d/w ratio is achieved with an addition of 140 ppm Se to the weld pool; the same change can be reached with 67 ppm S in the metal (a consequence of an addition of 750 ppm SO₂ to the shielding gas). A combination of inward and outward directed flows (double circulation loop) is also possible under certain circumstances, because the inward flow due to the electro-magnetic forces acts mostly in the bulk of the pool and the outward flow due to surface tension gradients acts mostly at the surface [2.5].

Fig. 2.3 Surface tension γ as function of temperature T for pure iron (curve A), iron containing sulphur (curve B) and iron containing oxygen (curve C) [2.10].
Heat flow during welding

Variations in specific mass

Because the specific mass of a fluid generally decreases with increasing temperature, the hotter metal at the center of the weld pool flows upward and the cooler metal near the edges of the weld pool sinks downward. Consequently, the resulting flow is outward directed. The driving force of this flow is the bouyancy force $F_b$:

$$F_b = -\rho \beta g (T - T_0)$$  \hspace{1cm} (2.6)

in which $\rho$, $\beta$, $g$, $T$ and $T_0$ are the density of the liquid metal, the thermal expansion coefficient of the liquid metal, the gravitational constant, the temperature of the liquid metal under the arc and the melting temperature, respectively.

Forces due to the plasma jet

Due to electro-magnetic forces in the arc plasma, a plasma jet is generated, which originates at the end of the electrode and flows towards the weld pool. The plasma jet, which can reach velocities of more than 200 m/s, causes a drag force along the surface of the weld pool and an outward directed flow is the result. The situation is schematically illustrated in Fig. 2.4.

Furthermore, the plasma jet, which is proportional to the square of the arc current, depresses the pool in the center and this causes an inward directed flow. However, the depression is very small for currents smaller than 300 A. Moreover, Lin and Eagar [2.12] found, with the help of an analytical model, that the surface depression in this current range is mostly caused by the inward directed flow due to the electro-magnetic forces. Only at currents over 500 A the plasma jet plays a role in surface depression.
Heat flow during welding

Fig. 2.4  Schematic illustration of the drag force due to the plasma jet on the surface of the weld pool.

Numerous investigations have been carried out, both theoretically and experimentally, to model the existing weld pool flow in practical welding situations on the basis of the mentioned driving forces [2.4, 2.5, 2.9-2.16]. It appears that the buoyancy force is negligibly small compared to the electro-magnetic force [2.16]. Furthermore, it has been found that the surface tension force dominates the electromagnetic force for currents below 150 A [2.9-2.11]. Under normal GTA welding conditions (I < 200 A) the plasma jet force is also negligibly small [2.12]. Mathematical modeling by Kou [2.4, 2.5], aimed at comparing the individual influences of the forces, has yielded an estimation of the maximum velocity occurring in the weld pool due to the individual forces: generally speaking, the velocity due to the buoyancy force is less than 1 cm/s, the velocity due to the electro-magnetic forces is less than 20 cm/s and the velocity due to the surface tension force can be more than 3 m/s. Thus, it can be concluded that the surface tension force is the dominant force in weld pool convection and, furthermore, that both the buoyancy force and the arc jet force are negligibly small under practical GTA welding circumstances.
2.5 Weld penetration problems

Weld pool convection is generally accepted as the major factor as far as the geometry of the weld is concerned. In fact it determines the d/w ratio and the penetration depth during GTA welding. Agreement exists that under normal GTA welding conditions (I < 200 A) Marangoni flow is the dominant flow, defining the convection flow pattern. The consequence of this is that the flow pattern and penetration depth are determined by the alloying elements and impurities present in the material. In the previous section it is shown that a sulphur content above 60 ppm can reverse the Marangoni flow pattern from outward to inward, resulting in a better geometry of the weld pool (larger d/w ratio). However, other steel properties are mainly negatively influenced by sulphur (for instance, it increases embrittlement and reduces mechanical properties because of segregation of FeS at the grain boundaries). Over the last decades there has been an enormous improvement in steel manufacturing and as a result of this, today’s high quality steels contain less than 10 ppm S. This improvement is in fact a negative development as far as welding is concerned, because the positive influence of sulphur on the surface tension gradient starts at about 60 ppm. Since the chances are small that low quality steel is being applied in high quality applications and assuming that a low sulphur content remains the trend, research and development in the field of arc welding is largely focused on improvement of equipment like pulsed power sources, servo systems and arc voltage control, because less weldable material is extremely sensitive to welding process variations and the smallest variation in welding parameters can cause penetration problems.

Recently, there is an increasing interest for research in the area of penetration sensing in order to eventually develop a system which controls the input (welding current) after inspection of quality aspects of the output (penetration depth). The next chapter will focus on the research in the area of penetration sensing and the results which have been achieved in this area so far.
Heat flow during welding

References

chapter 3

Sensors for weld penetration control

3.1 Introduction

Process sensing and control has become one of the key factors for research in welding technology. The reason for this is the large scale application of automatic and robotic welding units, which have to be equipped with sensing and control facilities in order to achieve some flexibility, inherent to manual welding.

The sensors which have been developed thus far were fitted to detect a wide range of errors and deviations like: work shape errors, setting errors, groove shape changes, tack beads, weld deformation and jig errors.

According to their use, sensors are classified as follows:

- seam tracking control of welds;
- adaptive control of welding conditions;
- seam tracking and adaptive control;
- weld monitoring.

Arc length and torch position control are the basis of these sensors. The types of arc length control that have been reported are:
Sensors for weld penetration control

- mechanical distance sensors;
- arc voltage control;
- capacitive distance sensors.

Torch position control is a special case of arc length control: the arc length is kept at maximum by means of horizontal displacement (instead of vertical) for seam tracking.

A category of sensing which is still in the laboratory stage of research is penetration sensing, although many claims have been made by researchers for new developments in this area.

In the next two sections the techniques, developed so far in the area of penetration sensing, will be discussed. Depending on the position of the sensor with respect to the weld pool, these techniques can be divided in two categories:

- backface sensing: sensing from the underside of the workpiece;
- topface sensing: sensing from the torch side.

Backface sensing can be seen as a direct method of penetration sensing, topface sensing is an indirect method. Table 3.1 gives a brief overview of the sensing techniques which will be described.

<table>
<thead>
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<th>topface sensing</th>
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<td>surface radiation sensing [3.1-3.5]</td>
<td>radiographic sensing [3.7, 3.8]</td>
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<td>shadow motion sensing [3.6]</td>
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<td></td>
<td>weld pool oscillation sensing [chapter 4]</td>
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</table>
3.2 Backface sensing

Although the application of backface sensing techniques is limited because in many constructions the backface of a weld is not accessible, there are a few techniques which have been developed and are being used with some success.

3.2.1 Radiation sensing [3.1-3.5]

In the case of radiation sensing, the radiation from the back surface of the weld is collected by an optical sensor (an optical fiber connected to a camera or an optical pyrometer camera). This radiation shifts to higher frequencies at higher temperatures; it can therefore be thresholded at the melting temperature of the workpiece and a fully penetrated weld pool can be detected.

The method can in principle be applied for all arc welding processes (including GTAW and GMAW), is simple to use and requires only a few initial preparations. The signal is not disturbed by the welding arc, but is sensitive to oxidation at the underside. The sensor must be calibrated for each type of material.

3.2.2 Shadow motion sensing [3.6]

Shadow motion sensing is based on the sagging of the weld pool, which occurs as soon as full penetration is reached. This sagging can be detected at the underside of the weld. As schematically illustrated in Fig. 3.1, a Ne/He laser beam is expanded to a 1 cm diameter beam. After passing beneath the weld pool the beam is focused on a photo-diode. The beam is partly blocked (shadowed) by the sagging weld pool. The sagging is proportional to the arc force (current). The shadow motion can therefore be modulated by current variations and the detected signal varies synchronously with the current.

The modulated signal can only be detected when the weld pool is fully penetrated. The method is therefore a reliable penetration sensor. However, it can only be used in the horizontal (flat) position. Another limitation is the difficulty to keep the sensing system moving in step with the torch.
Sensors for weld penetration control

weld pool

light beam

photodiode

Fig. 3.1 Schematic set-up of laser shadow motion method.

3.2.3 Radiographic sensing [3.7, 3.8]

Insufficient penetration can be detected by means of radiographic imaging: X-rays are reflected twice (at the bottom of the weld pool and at the underside of the workpiece) in the case of partial penetration; in the case of full penetration there is only one reflection. The resulting difference in intensity can be processed by a digital image processor and computer for feedback control (see Fig. 3.2).

Fig. 3.2 Schematic set-up of radiographic sensing method.
The method is applied in SMA welding. It has a fast response time (real-time penetration control) and high reliability. However, the equipment is large and expensive and sophisticated software for image digitization and analysis is required. Because in the radiographic imaging technique the X-ray source is located at the torch side of the workpiece, it is sometimes referred to as a topface sensing technique. However, the camera has to be located at the underside, which makes it more reasonable to group it among the backface sensing techniques.

3.3 Topface sensing

Topface sensing is not hampered by the disadvantage of inaccessibility which is characteristic for backface sensing. However, the sensing method is indirect and in most cases the sensing data are more difficult to interpret.

3.3.1 Ultrasonic sensing [3.9-3.14]

Both compression waves and shear waves can be used to interrogate the weld pool either in the transmission mode or in the pulse-echo mode; the time delay between input pulse and received echoes can give information about the geometry (penetration situation) of the weld by comparing with the signal prior to welding. Figure 3.3 gives a schematic illustration of the experimental arrangement of two ultrasonic sensing systems. As can be seen in this figure, the transducers are placed on both sides of the welding head: a compression probe (acting as transmitter) and a shear probe (pulse-echo) on one side and a compression probe on the other side to act as the receiver for transmitted compression waves (see Fig. 3.3a). The distance between the transmitter and receiver is kept constant throughout the whole process. The welding arc and the three transducers are all in line. The transducers move along with the welding head to act as an on-line weld monitor and ultrasonic coupling is achieved with a water irrigation system.
Fig. 3.3 Schematic set-up of ultrasonic sensing method with receiving probes for transmitted and reflected waves (a) and simplified version with only a receiving probe for transmitted waves (b).

The experimental arrangement can be simplified in the case of special applications. As can be seen in the example presented in Fig. 3.3b, one compression probe is mounted on one side as transmitter and another probe on the other side as receiver. A linear encoder is mounted on the welding head side and during welding ultrasonic data are acquired as the welding electrode moves along the weld groove. The ultrasonic signals are sent to a transient recorder and a computer for analysis and display. The signals can also be collected by a video system so that real-time ultrasonic signals can be displayed on screen, providing a convenient method to review the data during welding. Figure 3.4 shows an example in which the ultrasonic scans of the weld groove prior to and during welding are compared to determine the weld pool penetration of a root pass weld. It can be seen in this figure that good penetration is obtained when there is no echo from the bottom center of the welding groove.

Although the method can be used for most arc welding processes (GTAW, GMAW, SAW) it has many limitations caused by the complexity of the equipment: moving the transducers in step with the welding head and keeping good contact with the workpiece are the most problematic. However, progress has been made with the development of contactless transducers and laser sound generation [3.13, 3.14].
3.3.2 Surface temperature (infrared) sensing technique [3.15-3.18]

In the case of surface temperature sensing, an infrared camera is directed towards the weld bead to monitor the temperature gradient in the vicinity of the weld pool. The infrared frequency is chosen at a value where the intensity of the radiation generated by the arc is lower than the intensity of the radiation generated by the weld pool and surroundings.

The image is sent to a TV monitor and computer. Perturbations in weld penetration are visible in the temperature gradient. The image processing is rather complex, which makes the method not yet suitable for real-time application.
3.3.3 Trace element method [3.19, 3.20]

The trace element method is based on the fact that tracers are attached to the backface of the workpiece prior to welding, as depicted in Fig. 3.5. When weld penetration reaches the root, these tracers are melted and transferred to the weld pool surface under the action of convection in the weld pool. The tracers reaching the weld pool surface are detected by a spectral emission collector, connected with a computer for data handling. In the case of partial penetration, no tracer elements are transferred to the weld pool, and hence no emission of the tracer from the weld pool surface occurs.

The choice of a good tracer is the main problem in this method, the most important requirements being:

- it must generate sufficient emission of suitable wavelength;
- it must be easy to apply to the backface of the workpiece;
- no loss of tracer (by oxidation for instance) may occur before it is transferred to the molten material;
- it must have good solubility at the melting temperature of the material and a high partial vapor pressure at the surface temperature of the molten metal at the arc side;
- it must have no harmful effect on pool convection;
- it must have no harmful effect on the environment.

The deposition itself is also a problem in many cases (for instance, in pipe and tube welding) because of the inaccessibility of the backside of the workpiece.

Fig. 3.5 Schematic set-up of trace element method.
3.3.4 Sensing arc voltage variation due to surface sagging (weld pool depression) [3.21, 3.22]

When during welding the torch is kept at a fixed position above the workpiece, the sagging of a fully penetrated weld can be sensed by means of an arc voltage increase, which is proportional to the arc length increase (see Fig. 3.6). This method has a few advantages (it is cheap, no extra sensing element is needed), but also a number of shortcomings:

- it can only be applied in the flat position;
- a sagging weld bead is not appreciated in most circumstances, but is necessary for penetration sensing with this method;
- arc voltage variations due to other causes than surface sagging, like surface preparation or plate deformation, may give false information about the penetration.

Fig. 3.6 Schematic set-up of weld pool depression method.
3.3.5 Weld pool oscillation sensing

In the foregoing a description is given of the various penetration sensing systems which have been developed so far. An important drawback of all these systems (except the weld pool depression system) is that they are rather complex and in many cases require access to the backface of the workpiece. Many of the systems have also a negative effect on weld bead appearance (sagging). This hampers their application.

This thesis deals with an alternative approach to penetration sensing, which is based on weld pool oscillation. This approach is simple and straightforward (through-the-arc sensing) and opens possibilities for sensing over a wide range of applications. In fact, the weld pool oscillation method is the only method which gives direct information about the pool mass; when the weld pool is excited in oscillation then the oscillation frequency gives information about the penetration, the mass and the size of the weld pool.

In the next chapter a detailed description will be given of the theory of weld pool oscillation, including a model of the different oscillation modes which can occur.
References


Sensors for weld penetration control


chapter 4

Weld pool oscillation

4.1 Introduction

The weld pool convection flow, described in chapter 2, occurs under influence of constant or slowly changing forces. Rapidly changing and periodical external forces cause another type of liquid motion: weld pool oscillation.

Back in 1972 Kotecki et al. [4.1] suggested oscillatory behavior of the weld pool to explain the ripple formation in solidified stationary welds. In 1983 Renwick and Richardson [4.2] empirically determined the relation of an increasing oscillation frequency with decreasing weld pool size, using short current pulses to excite a stationary weld pool into oscillation and measuring the arc voltage response (which is linearly related to the arc length). Zacksenhouse and Hardt [4.3] measured the response of the underside of the weld pool to an alternating current, superimposed on the DC welding current and found the natural frequency to be corresponding to the size of the weld pool.

The first application of weld pool size control, based on the measurement of the weld pool natural oscillation frequency was reported by Madigan and Renwick [4.4]. Their welding system consisted of a feedback loop for current control, based on deviation from an empirically determined setpoint value of the oscillation frequency. Sorensen and Eagar [4.5] were the first to use Fast Fourier Transform (FFT) techniques for (off-line)
Weld pool oscillation

frequency analysis of arc voltage variations, caused by current pulses in stationary weld pools, although they reported a large uncertainty in relating the oscillation frequency to the weld pool size.
Salter and Deam [4.6] used an optical fiber, connected to the welding head, for intensity measurement to detect arc light modulation caused by changing arc length and a changing reflectivity of the weld pool surface. An advantage of arc light intensity measurement compared to arc voltage measurement, also reported by Yoo and Richardson [4.7], is the reduced sensitivity to anode and cathode conditions.
A sinusoidally varying arc current (superimposed on a DC base current) was used by Wang et al. [4.8, 4.9] to excite the weld pool into oscillation. They selected the frequency according to the expected size of the weld pool. In their approach the arc was moved stepwise along the seam. Welding was carried out only under static arc conditions (zero travel speed). Under these conditions the weld pool starts to grow from zero size until it reaches a size with a characteristic oscillation frequency equal to the applied frequency and resonance occurs, detected by means of a maximum in the arc voltage variation. Immediately after resonance starts to occur, the arc is moved to a next spot along the seam for the same procedure. The disadvantage of this method is that it is necessary that the characteristic frequency (expected weld pool size) has to be known exactly before the operation. Furthermore, it must be expected that resonance will give rise to upswing of the liquid metal in the weld pool, which in turn will result in a humping weld bead.
Tam and Hardt [4.10] used pulse modulated white noise in the input current. A resonance peak was expected to appear in the frequency spectrum at the characteristic frequency of the weld pool, but because of the limited band width in time domain the variance in frequency domain was too high for a reliable analysis.

4.2 Modeling weld pool oscillation

In theoretical modeling of weld pool oscillation several approaches have thus far proved to be more or less satisfactory. Zacksenhouse and Hardt [4.13] used a force equilibrium approach in which a force balance between pool mass, arc pressure and surface tension
was evaluated. For full penetration weld pools they found that the natural frequency can be expressed as:

$$f = \frac{0.173}{R} \frac{g}{\sqrt{\rho H}}$$

(4.1)

with $\rho$ the density of the liquid, $g$ the surface tension, $H$ the thickness of the workpiece and $R$ the radius of the weld.

Yoo [4.11] used the so-called Rayleigh energy approach to calculate the maximum values of the potential and kinetic energy of the system, which occur when the average displacement of the surface is at maximum and zero, respectively. Damping energy is taken into account both as viscous damping and as travel speed damping due to melting and solidification. Introducing a mode shape function for symmetric and sloshing full penetration, symmetric and sloshing partial penetration and symmetric transition penetration gives displacement functions for each of these oscillation modes, respectively. For full penetration the weld pool is represented by a tapered cylinder and for partial penetration by an ellipsoid with elliptical free surface. In the transition penetration mode the top surface is assumed to oscillate in the symmetric partial penetration mode, while the bottom surface is assumed to oscillate in the symmetric full penetration mode, in phase with the inner region of the top face motion. The partial penetration mode at the top face is supported by the tapered wall. The transition penetration mode displacement function equals the partial penetration mode when the bottom surface is zero and the full penetration mode when the bottom surface equals the top surface. Calculation of the natural frequency of the pool can be performed with the Rayleigh energy method, which is based on equalizing the maximum values of the kinetic and potential energy.

In a different approach, Yoo uses the maximum kinetic ($T_{\text{max}}$) and maximum potential ($U_{\text{max}}$) energy and incorporates these energies in a so-called lumped model, a model which can be expressed in terms of discrete mass, spring and damper, derived from weld pool equivalents (pool mass, surface tension, viscous damping and travel speed damping). This leads to the following equations for the equivalent mass $m_{\text{eq}}$, the equivalent spring constant $k_{\text{eq}}$ and the equivalent damping coefficient $c_{\text{eq}}$:

$$m_{\text{eq}} = \frac{2}{K^2 \omega^2} T_{\text{max}}$$

(4.2a)
Weld pool oscillation

\[ k_{eq} = \frac{2}{K^2} U_{max} \]  

\[ c_{eq} = \frac{1}{\pi K^2 \omega} (E_{vis} + E_{ts}) \]  

with \( K \) the maximum displacement, \( \omega \) the angular oscillation frequency, \( E_{vis} \) and \( E_{ts} \) the damping energy due to viscosity and travel speed, respectively.

The natural oscillation frequency can now be written as:

\[ \omega_n = \sqrt{\frac{k_{eq}}{m_{eq}}} \]  

and the resonance frequency can be calculated from the natural frequency by the equation:

\[ \omega_r = \omega_n \sqrt{1 - \varepsilon^2} \]  

with:

\[ \varepsilon = \frac{c_{eq}}{2 \sqrt{m_{eq} k_{eq}}} \]  

For practical situations \( \varepsilon \) can often be assumed to be zero so that the resonance frequency equals the natural frequency.

Yoo's experimental results prove the existence of a partial penetration oscillation mode, a full penetration oscillation mode and a transition oscillation mode. However, the transition mode was found to appear only in combination with the full penetration mode.
4.2.1 Potential flow model for partially penetrated weld pools

Maruo and Hirata [4.12] introduced a model for irrotational liquid motion in a circular basin of diameter D and depth h under influence of a disturbing force. The model has been further developed by Xiao [4.13] for the general case of elliptic weld pools. The motion of the liquid is given by the Laplace equation:

\[ \Delta \Phi = 0 \quad (4.6) \]

with \( \Phi \) the velocity potential and with boundary conditions \( \partial \Phi / \partial z = 0 \) at \( z = h \) and \( \Phi = 0 \) at \( r = D/2 \).

In cylinder co-ordinates equation (4.6) takes the form:

\[ \frac{\partial^2 \Phi}{\partial r^2} + \frac{1}{r} \frac{\partial \Phi}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \Phi}{\partial \theta^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0 \quad (4.7) \]

**Partially penetrated circular weld pools**

In stationary welding, the weld pool is rotationally symmetric and therefore the \( \partial^2 \Phi / \partial \theta^2 \) term in equation (4.7) equals zero. Via separation of variables the general solution of equation (4.7) can now be obtained, which results in the following equation:

\[ \Phi = AJ_0 (kr) \left( B_1 e^{kr} + B_2 e^{-kr} \right) \cos (\omega t + \omega_0) \quad (4.8) \]

in which \( A, B_1, B_2, k \) and \( \omega_0 \) are constants, \( J_0 \) is the first kind zero order Bessel function and \( \omega \) the angular oscillation frequency.

If \( \xi \) is the vertical displacement of the surface with respect to its equilibrium position, then the pressure difference between the two sides of the surface \( (p - p_0) \) can be written as:
Weld pool oscillation

\[ p - p_0 = -\gamma \left( \frac{1}{r^2} \frac{\partial \xi}{\partial t} + \frac{\partial^2 \xi}{\partial \alpha^2} \right) \quad (4.9) \]

with \( \gamma \) the surface tension. For potential flow \( p \) can be rewritten as:

\[ p = -\rho_l \, g \, \xi - \rho_l \, \frac{\partial \phi}{\partial t} \quad (4.10) \]

with \( \rho_l \) the density of the liquid metal and \( g \) the gravitational constant. Substituting equation (4.10) into equation (4.9) gives:

\[ \rho_l \, g \, \xi + \rho_l \, \frac{\partial \phi}{\partial t} + p_0 - \gamma \left( \frac{1}{r^2} \frac{\partial \xi}{\partial \alpha} + \frac{\partial^2 \xi}{\partial \alpha^2} \right) = 0 \quad (4.11) \]

The boundary condition at the surface (\( z = 0 \)) is obtained by differentiating equation (4.11) with respect to time and replacing \( \partial \xi/\partial t \) by \( \partial \phi/\partial z \) (the normal component of the fluid velocity at the surface must be equal to the velocity of the surface itself). With equation (4.8) and the boundary condition at \( z = h \), the angular oscillation frequency can be expressed as:

\[ \omega^2 = \left( gk + \frac{\gamma}{\rho_l} \, k^3 \right) \tanh(2kh) \quad (4.12) \]

To satisfy the boundary condition at \( r = D/2 \), it is necessary that \( J_\theta(kD/2) = 0 \). The roots satisfying this condition are: \( kD/2 = 2.405, \ 5.520, \ 8.654, \ ... \) The dominant oscillation mode (see Fig. 4.1) is the mode with \( kD/2 = 5.52 \). This mode is called mode 1. With \( \omega = 2\pi f \) equation (4.12) can now be rewritten as:

\[
\text{mode 1} \quad f^2 = \frac{1}{4\pi^2} \left( \frac{11.04}{D} \, g + \frac{1345.5}{D^3} \, \frac{\gamma}{\rho_l} \right) \tanh \left( \frac{22.08}{h} \frac{h}{D} \right) \quad (4.13)
\]
Weld pool oscillation

![Diagram showing top and side views of a weld pool]

Fig. 4.1 Dominant oscillation mode in circular, partially penetrated weld pool: mode 1 [4.13].

**Partially penetrated elliptical weld pools**

The weld pool formed during traveling arc welding is not circular but elliptical. Consequently, the simplification $\frac{\partial^2 \Phi}{\partial \theta^2} = 0$ is not valid, which makes the solution of the Laplace equation less straightforward.

The general solution of the Laplace equation is:

$$\Phi = A J_n(kr) \left( B_1 e^{kx} + B_2 e^{-kx} \right) \cos(\omega t + \omega_0) \cos(n \theta + \theta_0) \quad (4.14)$$

with $J_n$ the first kind $n^{th}$ order Bessel function ($n = 0, 1, ...$). The solution of equation (4.14) takes the same form as equation (4.12). However, in this case $k$ is determined by $J_n(kD_{eq}/2) = 0$ with $D_{eq}$ the equivalent diameter of the elongated weld pool.

Figure 4.2 shows the dominant oscillation modes in an elliptical weld pool. For $J_0$ the dominant mode occurs when $kD_{eq}/2 = 5.520$, the same value as for stationary weld pools, corresponding to mode 1. For $J_1$ the dominant mode occurs when $kD_{eq}/2 = 3.832$, giving an extra oscillation mode for elliptical weld pools.

The oscillation frequency for this extra mode (mode 2) can, similar to equation (4.13), be written as:

$$f^2 = \frac{1}{4\pi^2} \left( \frac{7.66}{D_{eq}} g + \frac{449 \gamma}{D_{eq}^3 \rho} \right) \tanh \left( 15.32 \frac{h}{D_{eq}} \right) \quad (4.15)$$

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Weld pool oscillation

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Fig. 4.2 Dominant oscillation modes in elliptical, partially penetrated weld pool: mode 1 (a) and mode 2 (b) [4.13].

### 4.2.2 Membrane model for fully penetrated weld pools

Maruo and Hirata [4.14] used the potential flow approach for modeling oscillation in fully penetrated weld pools, either circular or elliptical. Their solution leads to the following expression for the angular oscillation frequency:

\[
\omega^2 = \left( -\frac{gk}{\rho} + \frac{\gamma k^3}{\rho} \right) \frac{\sinh(kh)}{\cosh(kh) - 1}
\]  

(4.16)

To determine the value of \( k \) it is possible to insert: \( \phi = \phi_0 (\alpha e^{kz} + \beta e^{-kz}) \cos \omega t \) into the Laplace equation, which yields the following differential equation of the Helmholtz type:

\[
\nabla^2 \phi_0 + k^2 \phi_0 = 0
\]  

(4.17)
For the solution of equation (4.17) a finite difference approximation can be applied, which results in an eigenvalue problem, yielding the different oscillation modes.

An analytical method which can be applied in the case of full penetration welding, is the so-called membrane approach, first proposed by Kotecki et al. [4.1] and further modified by Xiao [4.13]. In this approach the motion of the weld pool is regarded as the motion of a membrane, following the two-dimensional wave equation:

$$\frac{\partial^2 \phi}{\partial t^2} = \frac{\Gamma}{m} \Delta \phi$$  \hspace{1cm} (4.18)

with $\Gamma$ the surface energy and $m$ the mass of the liquid metal in the weld pool.

For circular weld pools equation (4.18) can be expressed in cylinder co-ordinates and the solution is:

$$\phi = AJ_0(kr) \cos \left( k \left( \frac{\Gamma}{m} \right)^{\frac{1}{2}} t + C \right)$$  \hspace{1cm} (4.19)

with $A$ and $C$ constants. For harmonic oscillations it is necessary that:

$$k \left( \frac{\Gamma}{m} \right)^{\frac{1}{2}} T = 2\pi$$  \hspace{1cm} (4.20)

with $T = 1/f$.

Using $\Gamma = 2\pi \left( \frac{D}{2} \right)^2 \gamma$ and $m = \pi \left( \frac{D}{2} \right)^2 H\rho_l$, the lowest order mode oscillation frequency for fully penetrated weld pools, corresponding with the situation illustrated in Fig. 4.3, can be obtained by taking $kD/2 = 2.405$ (the lowest order root of $J_0$). This yields the oscillation frequency of the dominant mode (mode 3) for full penetration:

$$f = 1.08 \left( \frac{\gamma}{H\rho_l} \right)^{\frac{1}{2}} D^{-1}$$  \hspace{1cm} (4.21)
Weld pool oscillation

<table>
<thead>
<tr>
<th>top view</th>
<th>side view</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4.3 Dominant oscillation mode in fully penetrated weld pool: mode 3 [4.13].

4.3 Evaluation of the oscillation modes

When considering equations (4.13) and (4.15) it is appropriate to introduce some simplifications to make the equations more convenient. The first simplification is to substitute \( \tanh(22.08h/D) \) and \( \tanh(15.32h/D_{eq}) \) by the value 1, which is a reasonable approximation for real welding situations \( (h > 0.2D) \). Furthermore, the influence of gravitation can be neglected; the error made by doing so is less than 3% for mode 1 and less than 6% for mode 2 with pools smaller than 10 mm diameter (see Fig. 4.4). The simplified expressions for the oscillation frequency can now be written as:

**mode 1**

\[
f = 5.84 \left( \frac{\gamma}{\rho_l} \right)^{\frac{1}{2}} D^{\frac{1}{3}}
\]  

(4.22)

**mode 2**

\[
f = 3.37 \left( \frac{\gamma}{\rho_l} \right)^{\frac{1}{2}} D^{\frac{1}{3}}
\]  

(4.23)

In order to compare the magnitude of the three oscillation modes, some frequency calculations have been carried out for iron \( (\gamma = 1.872 \text{ N/m}; \rho_l = 7.03 \cdot 10^3 \text{ kg/m}^3 ) \). The calculated frequencies are shown in Fig. 4.5 as function of the weld pool diameter. It can be seen in this figure that there is a significant difference in frequency between the three
oscillation modes, especially for small pool diameter. In other words, it is possible to distinguish between the three oscillation modes by measuring the oscillation frequency. Oscillation mode 2 needs some further explanation. This mode is the so-called sloshing mode which leads to an undesirable situation because of the resulting irregular (humping) weld bead appearance [4.12]. Mode 2 can be avoided by reducing the travel speed (<15 cm/min). In the next section further details will be given about the selection of process conditions which are favorable for mode 1 and mode 3 oscillation and reduce mode 2 oscillation.

Fig. 4.4 Relative error for mode 1 oscillation and mode 2 oscillation as function of weld pool diameter when neglecting the gravity effect [4.13].

Fig. 4.5 Frequencies for three different oscillation modes (mode 1, mode 2 and mode 3) as function of weld pool diameter [4.13].
4.4 Weld pool oscillation as tool for penetration sensing

The difference between the oscillation frequencies of mode 1 and mode 3 can be used as a basis of weld penetration sensing, a concept which has been investigated by Xiao [4.13]. The essential element of this concept is that the transition from partial to full penetration is accompanied by an abrupt change in frequency (see Fig. 4.6). The moment this transition occurs, coincides with the moment the bottom diameter of the weld becomes larger than about 1.2 times the plate thickness [4.13]. The oscillations of the weld pool can be triggered with a short current pulse (theoretically a $\delta$ pulse) superimposed on the welding current. A $\delta$ pulse contains all frequencies (a horizontal line in the frequency domain), which means that also the characteristic frequency of the weld pool is included and resonance can occur. The arc pressure (proportional with $I^2$) during the current pulses causes a depression of the weld pool surface. After release of this pressure the surface tends to move to its equilibrium position which gives rise to a damped oscillation.

![Graph showing oscillation frequency versus base current](image)

Fig. 4.6 Oscillation frequency versus base current, showing the transition from mode 1 to mode 3 when the penetration passes from partial to full [4.13].
By measuring the arc voltage during oscillation of the weld pool, it is possible to detect the oscillation frequency. This approach is based on the fact that the arc voltage is proportional to the arc length (ΔV = EΔl, with E the electric field strength of the arc plasma). With fixed electrode (GTA welding) the arc voltage is thus proportional to the relative height of the pool surface. The voltage is recorded during welding and after welding frequency analysis (FFT) is carried out. The difference between mode 1 and mode 3 oscillations can easily be observed in the arc voltage variations or, after FFT analysis, in the frequency spectrum (see Fig. 4.7).

The most important limitation of weld pool oscillation sensing is the maximum travel speed, which is about 15 cm/min under normal welding conditions; at larger travel speed mode 2 oscillation will start to occur. A magnetic deflection system can be used [4.22] to keep the arc centered above the pool to avoid mode 2 oscillations in the case of high travel speed.

![Graphs showing arc voltage and current variations with frequency spectrum](a) and (b)

Fig. 4.7  Time sample of arc voltage and arc current and corresponding frequency spectrum for mode 1 oscillation (a) and mode 3 oscillation (b).
Weld pool oscillation

Other limitations of weld pool oscillation sensing concern the shielding gas, the arc length and the geometry of the electrode.

- Helium rather than argon should be used as shielding gas: the electric field strength in an helium arc is higher (1-4 V/mm) than in an argon arc (0.5-1 V/mm), which makes the arc voltage method more sensitive for arc length variations when helium is used [4.13, 4.23].

- The arc length should be kept small (< 2 mm) because mode 2 oscillations are more likely to occur at large arc length and the sensitivity for triggering is better at small arc length [4.13, 4.24].

- The electrode diameter and the electrode tip angle must be small (< 3.2 mm and < 40°, respectively) to make effective triggering of the oscillations possible [4.13, 4.25, 4.26].

Some of the limitations mentioned above do not play a role when light emitted by the arc is used to sense the weld pool oscillation [4.7]. However, this technique needs an extra sensing element (glass fiber) which has to fit in the welding head and fills part of the scarce space available. Arc light sensing can also be problematic because of heat production and dust formation in the vicinity of the welding head.

A specific drawback of the weld pool oscillation sensing technique is that with this technique only the transition between partial penetration and full penetration (and vice versa) can be detected and that it does not provide information about the degree of full penetration. However, in many situations it is demanded to keep the full penetration restricted and preferably as small as possible. An appropriate way to obtain information about the degree of full penetration is to make use of pulsed welding current, a technique which shall be dealt with in the next chapter.
Weld pool oscillation

References

4.1 D.J. Kotecki, D.L. Cheever and D.G. Howden (1972), "Mechanism of ripple formation during weld solidification", Welding Journal, 51(8), p 386s-391s


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Weld pool oscillation

chapter 5

Weld pool oscillation during pulsed GTA welding

5.1 Introduction

In GTA welding an arc is burning between a non-consumable electrode and the workpiece to be welded. In most cases a constant welding current is used. A specific variant of GTA welding is the pulsed GTA welding process, introduced in the late 60’s and now widely applied. It has a number of specific advantages compared to constant current welding and is often used when full penetration is required, like root pass welding of thick material or single pass welding of thin material. The pulsed GTAW process is the standard choice for out-of-position welding, especially for orbital tube and pipe welding. Several researchers have claimed positive results when applying pulsed current welding [5.1-5.6]. These claims concern: reduction of the total heat input; an increased weld bead depth-to-width (d/w) ratio and a narrower heat-affected zone; reduction of grain size; increase of penetration; reduction of porosity; thinner material can be welded; improved tolerance to heat sink variations; reduced tendency to hot cracking and an increased arc stability.
Weld pool oscillation during pulsed GTA welding

In pulsed GTA welding, the welding current alternates repeatedly between two levels: the pulse current and the base current. The average current can usually be maintained at a lower level than required with constant current welding for the same penetration depth. This chapter deals with the role of weld pool oscillation in pulsed GTA welding. Specific attention will be given to the possibility to use weld pool oscillations for sensing and in-process control of weld penetration.

5.2 Pulsed GTA welding

In constant current GTA welding there are two parameters which control the heat input: welding current and travel speed. In pulsed GTA welding the heat input is controlled by the following five parameters (see Fig. 5.1):

- travel speed;
- pulse current $I_p$;
- base current $I_b$;
- pulse time $t_p$;
- base time $t_b$.

Fig. 5.1 Pulse parameters for pulsed GTA welding ($I_p = \text{pulse current}, I_b = \text{base current}, t_p = \text{pulse time}, t_b = \text{base time}$).
Weld pool oscillation during pulsed GTA welding

The current pulses can be rectangular, but in most cases have a small up-slope and down-slope and are generally kept at low frequency (1-5 Hz). In the past also triangular, sawtooth or sinusoidal pulses have been used. Most researchers [5.1-5.3, 5.6, 5.7] claim that the best penetration depth of the weld is obtained with low pulse frequencies. Nevertheless, Saedi and Unkel [5.4] report positive results with sinusoidal pulses at high frequencies (> 3000 Hz).

Usually the travel speed is kept at a constant level. However, Wang et al. [5.8, 5.9] applied a stepper motor in order to obtain a pulsed travel speed, synchronously with the current pulses.

Due to the high current I_p during the pulse time t_p the material melts and forms an elliptical weld pool. The low current I_b during the base time t_b does not contribute to melting of the material, but is sufficiently high to maintain the arc. In fact, the size of the elliptical weld pool decreases considerably during t_b as a consequence of solidification.

Since the welding energy supplied to the workpiece is proportional to the current, the major part of the welding energy is generated during the pulse time. Research [5.4] has shown that during welding convection flow of the liquid metal occurs in the weld pool and that during the pulse time this convection flow is of type B (Fig. 2.2): the inward directed electro-magnetic forces dominate the weld pool convection flow when the pulse current is sufficiently high, causing a significant increase in penetration depth; in other words: in the case of pulsed welding a lower average current can be applied for the same penetration depth.

A basic feature of pulsed GTA welding is that under ideal conditions full penetration is achieved during t_p, whereas partial penetration is achieved during t_b. The pulse parameters provide a flexible way to control the energy input to the material and consequently the degree of penetration. The combination of pulse parameters and travel speed determines the weld overlap as is schematically shown in Fig. 5.2. The overlap of the subsequent pools must be sufficiently large in order to achieve complete penetration, which can be understood with the help of Fig. 5.3. This figure shows a situation of locally incomplete penetration, caused by a (too) high travel speed even though the individual weld pools are fully penetrated. An example of an aid for the selection of optimal pulse parameters is given in Fig. 5.4 [5.10].
Weld pool oscillation during pulsed GTA welding

Generally speaking, optimum weld quality during pulsed GTA welding is obtained at:
- high pulse current;
- low base current;
- low pulse frequency;
- low travel speed.

Fig. 5.2 Overlap of subsequent spot welds: horizontal cross-section top side (a), longitudinal cross-section (b) and horizontal cross-section bottom side (c).

Fig. 5.3 Horizontal cross-section top side (a), longitudinal cross-section (b) and horizontal cross-section bottom side (c) of weld, showing insufficient weld overlap between subsequent spot welds.
For each specific case the exact values of the welding parameters have to be determined empirically. These parameters are also dependent on material properties and on the size and geometry of the workpiece. In the case of orbital tube welding, for instance, the welding parameter setting is determined by orbital velocity, material properties and both the tube wall thickness and the diameter of the tube. The heat accumulation (heat input minus heat output) has also to be taken into account.

Fig. 5.4  Nomograph for the selection of pulse parameters for GTA welding of austenitic stainless steel [5.10].

5.3 The role of weld pool oscillation in pulsed GTA welding

Although the application of pulsed GTA welding generally results in an improvement of weld penetration, there is still a considerable chance that deviations from the ideal full penetration situation (Fig. 5.5a) occur during welding. These deviations can be due to variations in the workpiece dimensions, cast-to-cast variations in the chemical composition of the workpiece and unpredictable accumulation of heat in the workpiece. Each of these effects can give rise to either incomplete (partial) penetration (Fig. 5.5b) or
Weld pool oscillation during pulsed GTA welding

overpenetration (Fig. 5.5c). In the case of incomplete penetration, part of the seam will be left unwelded, which can considerably reduce the strength and the corrosion resistance of the joint. In the case of overpenetration excessive sagging of the liquid weld metal will occur, also reducing the strength of the joint. Although a little overthickness of the weld (reinforcement) at the top side is appreciated and in many cases required, bulging at the underside (sagging) should be avoided as much as possible. Sagging can ultimately result in burn-through.

Fig. 5.5 Schematic illustration of correct penetration (a), underpenetration (b) and overpenetration (c).

Thus it is clear that also in the case of pulsed welding there is a need for penetration sensing and control. The most promising approach is the weld pool oscillation sensor concept, developed by Xiao [5.11] and described in chapter 4. This sensor concept is based on a mode transition when passing from partial to full penetration (from mode 1 to
mode 3) or vice versa, which is accompanied by an abrupt change of the oscillation frequency.

When applying this sensor concept for pulsed welding, three different situations can be distinguished, depending on the particular welding situation.

In the case of correct welding, full penetration occurs during the pulse time and partial penetration during the base time (see Fig. 5.5a). In the case of incorrect welding either underpenetration (partial penetration during both the pulse time and base time, see Fig. 5.5b) or overpenetration (full penetration during both the pulse time and base time, see Fig. 5.5c) occurs.

This means that correct welds are obtained when the weld pool oscillates in mode 3 during \( t_p \) and in mode 1 during \( t_b \). For incorrect welding there are two possibilities:

- mode 3 oscillation during both \( t_p \) and \( t_b \), which is an indication of overpenetration;
- mode 1 oscillation during both \( t_p \) and \( t_b \), which is an indication of underpenetration.

On the basis of the foregoing it is now possible to define the principles of weld pool oscillation sensing in the case of pulsed GTA welding.

These principles are summarized in Table 5.1 and can be briefly formulated as follows: correct penetration occurs when two frequency peaks appear in the oscillation frequency distribution, underpenetration occurs in the case of one peak of high frequency and overpenetration occurs in the case of one peak of low frequency.

To verify the validity of these principles, a number of experiments was carried out under various experimental conditions. These experiments are discussed below.
Weld pool oscillation during pulsed GTA welding

Table 5.1  Oscillation frequency distribution for underpenetration, correct penetration and overpenetration

<table>
<thead>
<tr>
<th></th>
<th>pulse time</th>
<th>base time</th>
</tr>
</thead>
<tbody>
<tr>
<td>underpenetration</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td></td>
<td>high frequency peak</td>
<td>high frequency peak</td>
</tr>
<tr>
<td>correct penetration</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td></td>
<td>low frequency peak</td>
<td>high frequency peak</td>
</tr>
<tr>
<td>overpenetration</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td></td>
<td>low frequency peak</td>
<td>low frequency peak</td>
</tr>
</tbody>
</table>

5.4 The generation of oscillations

In the experimental work carried out by Xiao [5.11] dealing with weld pool oscillation in the case of constant current welding, the oscillations are generated by short current pulses, superimposed on the welding current. The energy input in the workpiece is merely carried by the constant welding current, whereas the pulse has no significant contribution to the energy input. The pulse is kept short and high in an attempt to approach the theoretical δ pulse, which is the ideal pulse form for generating weld pool oscillations. In pulsed GTA welding, as described in section 5.1, the pulse carries the larger part of the energy input and is therefore mainly responsible for melting of the material. The pulse
Weld pool oscillation during pulsed GTA welding

height and duration required in a specific situation are determined by the material properties and the dimensions of the workpiece. Either the up-slope or the down-slope of the pulse can trigger the oscillations in the weld pool. In fact, the weld pool "sees" the pulse as a step function, which is either an up-slope or a down-slope, except in the case of very short pulses (few ms) when the pulse approaches the theoretical $\delta$ pulse. In the frequency domain the $\delta$ function is real and constant (see Fig. 5.6a). An up-slope or down-slope in the frequency domain is imaginary and inversely proportional to the frequency (see Fig. 5.6b). The sensitivity for triggering is therefore constant for all frequencies in the case of a $\delta$ function and inversely proportional to the frequency in the case of a step function.

A consequence of this is that mode 3 oscillations, which are low in frequency, can quite easily be generated with a step function, while mode 1 oscillations, which are high in frequency, are more difficult to be generated. The duration of each of the periods $t_p$ and $t_b$ must be at least one period of the mode 3 oscillation in order to make a frequency analysis possible.

![Diagram](image)

Fig. 5.6b Fourier transform of a $\delta$ function (a) and of a step function (b).
Weld pool oscillation during pulsed GTA welding

More freedom in the choice of the pulse parameters can be achieved when the triggering of the oscillation is decoupled from the welding process; in other words: when the trigger pulses and welding pulses are made independent. Figure 5.7 gives an example of a pulse shape in which extra trigger pulses (δ pulses) are superimposed on the welding pulses. The length and height of both the trigger pulse and the welding pulse can independently be adjusted. For decoupling of triggering and welding it is necessary that \( I_t \ll I_p \) (the welding energy carried by the trigger current must be negligibly small compared to the welding energy carried by the pulse current), whereas the arc pressure, which is proportional to \( I^2 \), must be sufficiently large for triggering.

![Diagram](image_url)

**Fig. 5.7** Pulse parameters for pulsed GTA welding with extra trigger pulses (\( I_p \) = pulse current, \( I_b \) = base current, \( t_p \) = pulse time, \( t_b \) = base time, \( I_t \) = trigger current, \( t_t \) = trigger time).
Weld pool oscillation during pulsed GTA welding

5.5 Experiments

To test the oscillation behavior of the weld pool during pulsed GTA welding, experiments were performed both with normal current pulses, shown in Fig. 5.1, and with extra current pulses, shown in Fig. 5.7. The welding experiments were carried out with an Elma Hybrid 400 Inverter type power source, equipped with in-house built computer control. A software program was written to supply the power source with a variety of special pulse shapes, the one shown in Fig. 5.7 included. During welding the arc voltage was continuously measured and the frequency spectrum was calculated from the voltage variations by means of FFT (Fast Fourier Transform) analysis, using a computer program. The material used in the welding experiments was steel Fe 360 in the form of plates of 3 and 4 mm thickness. The chemical composition of the steel is given in Table 5.2.

<table>
<thead>
<tr>
<th>thickness</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>O</th>
<th>Cr</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 mm</td>
<td>0.074</td>
<td>0.04</td>
<td>0.32</td>
<td>0.017</td>
<td>0.014</td>
<td>0.0135</td>
<td>0.09</td>
<td>0.04</td>
</tr>
<tr>
<td>4 mm</td>
<td>0.094</td>
<td>0.04</td>
<td>0.54</td>
<td>0.017</td>
<td>0.009</td>
<td>0.0089</td>
<td>0.09</td>
<td>0.04</td>
</tr>
</tbody>
</table>

The welding conditions which increase the sensitivity for generation and detection of oscillations as determined by Xiao [5.11] (see section 4.4) are:
- low travel speed (< 15 cm/min);
- short arc length (< 2 mm);
- small electrode diameter (< 3.2 mm);
- small electrode tip angle (< 40 °);
- helium as shielding gas.

The welding conditions used in the various experimental situations were selected in line with these recommendations and are given in Tables 5.3 and 5.4.
Weld pool oscillation during pulsed GTA welding

In order to experimentally examine the three different oscillation situations, which occur in the case of underpenetration, correct penetration and overpenetration, experiments with different heat input were carried out with the 3 mm plates, with both normal pulses (Table 5.3a) and extra pulses (Table 5.3b).

<table>
<thead>
<tr>
<th>electrode material</th>
<th>tungsten, 2% thoria</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrode diameter</td>
<td>2.4 mm</td>
</tr>
<tr>
<td>electrode top angle</td>
<td>25°</td>
</tr>
<tr>
<td>arc length</td>
<td>1 mm</td>
</tr>
<tr>
<td>travel speed</td>
<td>7.5 cm/min</td>
</tr>
<tr>
<td>shielding gas</td>
<td>He, 24 l/min</td>
</tr>
<tr>
<td>purging gas</td>
<td>Ar, 3 l/min</td>
</tr>
</tbody>
</table>

**Table 5.3 Welding conditions for experiments with 3 mm plate**

<table>
<thead>
<tr>
<th>penetration</th>
<th>under</th>
<th>correct</th>
<th>over</th>
</tr>
</thead>
<tbody>
<tr>
<td>pulse current (A)</td>
<td>100</td>
<td>120</td>
<td>145</td>
</tr>
<tr>
<td>base current (A)</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>total cycle time (ms)</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>pulse time (ms)</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>base time (ms)</td>
<td>930</td>
<td>930</td>
<td>930</td>
</tr>
</tbody>
</table>

**a: normal pulses**

<table>
<thead>
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<th>correct</th>
<th>over</th>
</tr>
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<tbody>
<tr>
<td>pulse current (A)</td>
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<td>base current (A)</td>
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<tr>
<td>pulse trigger current (A)</td>
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<td>base trigger current (A)</td>
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<td>200</td>
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<td>pulse time (ms)</td>
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</tr>
<tr>
<td>base time (ms)</td>
<td>930</td>
<td>930</td>
<td>930</td>
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</tbody>
</table>

**b: extra pulses**
Attempts were also made to reveal the three oscillation situations corresponding with underpenetration, correct penetration and overpenetration subsequently during one welding run (constant heat input). By welding at sufficiently low travel speed and making use of the heat accumulation in the workpiece this situation was created during transition experiments with a 4 mm plate (Table 5.4).

Table 5.4 Welding conditions for experiments with 4 mm plate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
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<tbody>
<tr>
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<td>arc length</td>
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<td>purging gas</td>
<td>Ar, 3 l/min</td>
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<td>pulse current (A)</td>
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<td>base current (A)</td>
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<tr>
<td>total cycle time (ms)</td>
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</tr>
<tr>
<td>pulse time (ms)</td>
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</tr>
<tr>
<td>base time (ms)</td>
<td>900</td>
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</tbody>
</table>
Weld pool oscillation during pulsed GTA welding

5.6 Results

Following the procedure outlined above a large number of welding experiments was carried out. During welding both the arc current and arc voltage were continuously measured as a function of time.

In Figs. 5.8 and 5.9 the results of the 3 mm plate welding experiments, carried out under the welding conditions given in Table 5.3a (triggering with normal pulses) are presented. Figure 5.8a shows a time interval of the arc voltage and arc current recording in the underpenetration situation. It can be seen that mode 1 oscillation occurs both during the pulse time and during the base time. The situation of correct penetration is presented in Fig. 5.8b. The figure shows that mode 3 oscillation occurs during the pulse time, whereas mode 1 oscillation occurs during the base time. In Fig. 5.8c a time interval of the overpenetration situation is shown. Both during the pulse time and the base time mode 3 oscillation occurs.

Frequency spectra were calculated off-line, using the FFT algorithm, from the voltage samples, directly after the up-slope for \( t_p \) and directly after the down-slope for \( t_b \). The frequency resolution is 15.6 Hz (calculated from 128 voltage samples at a sample frequency of 2000 Hz).

In Fig. 5.9 the frequency spectra corresponding with the pulse time and the base time for the situations shown in Fig. 5.8 are presented. Figure 5.9 shows that

- in the case of underpenetration peaks of high frequency occur both for the pulse time and the base time (Fig. 5.9a);
- in the case of correct penetration a low frequency peak occurs for the pulse time and a high frequency peak for the base time (Fig. 5.9b);
- in the case of overpenetration peaks of low frequency occur both for the pulse time and the base time (Fig. 5.9c).

These observations are consistent with the predictions formulated in section 5.3.
Weld pool oscillation during pulsed GTA welding

Fig. 5.8 Time sample of arc current and arc voltage using normal current pulses, corresponding with a situation of underpenetration (a), correct penetration (b) and overpenetration (c).
Fig. 5.9 Frequency spectra corresponding with the situations of Fig. 5.8.
Weld pool oscillation during pulsed GTA welding

Fig. 5.10  Time sample of arc current and arc voltage using extra current pulses, corresponding with a situation of underpenetration (a), correct penetration (b) and overpenetration (c).
Weld pool oscillation during pulsed GTA welding

Fig. 5.11 Frequency spectra corresponding with the situations of Fig. 5.10.
The results of a series of similar experiments, carried out with extra trigger pulses, are presented in Figs. 5.10 and 5.11 (welding conditions listed in Table 5.3b). It appears that the results of this series are basically the same as those of the first series. Apparently, the way of triggering does not affect the frequency distribution of the oscillation modes. However, the amplitude of the oscillations is much higher when triggering with extra trigger pulses (especially for mode 1 oscillations).

Also the scatter in frequency in the case of triggering with normal pulses is considerably larger than in the case of triggering with extra pulses, especially in the underpenetration and correct penetration situations. This is reflected by the width of the frequency peaks (compare Figs. 5.9 and 5.11). The difference in scatter is a consequence of the low amplitude of the mode 1 oscillation when triggering with normal pulses compared to triggering with extra pulses, which makes the frequency spectrum more irregular (low signal to noise ratio). In the overpenetration situation (Fig. 5.10c) this difference in scatter is much smaller because for mode 3 oscillation the amplitude difference is less pronounced. These observations are in line with the considerations formulated in section 5.4.

A typical example of the results, obtained in the transition experiments is presented in Fig. 5.12. Figure 5.12a gives a plot of the oscillation frequency as a function of distance and shows that the weld pool changes gradually from underpenetration via correct penetration to overpenetration. The oscillation frequency remains high during underpenetration (mode 1) and remains low during overpenetration (mode 3) but switches between high and low, synchronously with the current pulses, during correct penetration (mode 1 / mode 3). This figure clearly shows that incorrect penetration is characterized by a single mode oscillation (mode 1 for underpenetration or mode 3 for overpenetration), whereas correct penetration is characterized by a mode switch (mode 3 during the pulse time and mode 1 during the base time).

In Fig. 5.12b the data of Fig. 5.12a are presented in the form of a plot of the sum frequency (defined as the sum of the oscillation frequency during the pulse time and the oscillation frequency during the base time) as a function of distance. The use of the sum frequency as parameter has the advantage that direct information is obtained about the overall degree of penetration during the total cycle time.
Weld pool oscillation during pulsed GTA welding

Fig. 5.12  Oscillation frequencies as a function of distance (a) and sum frequency as a function of distance (b), showing the transition from underpenetration, via correct penetration to overpenetration.
5.7 Prospects for weld penetration sensing

In the experiments described above the arc voltage and arc current were continuously measured during welding and digitally recorded. For frequency analysis a software program was written to apply the FFT algorithm on a representative number of voltage samples of the subsequent pulses for both pulse time and base time. After frequency analysis the weld is characterized by frequency peaks, which provide information about the degree of penetration. In the case of correct welding the frequency peaks are caused by mode 1 oscillation during \( t_b \) alternated with mode 3 oscillation during \( t_p \). This results in a time / frequency plot, which shows a fluctuation between high and low frequency for each period. On the basis of the results obtained, it can be concluded that sensing of weld pool geometry during pulsed current GTA welding is possible by monitoring the peaks in the frequency distribution: correct penetration welds are obtained when two peaks appear in the frequency distribution. Deviations from correct penetration can be sensed within one pulse cycle, which corresponds with a time resolution of 1 s when the pulse frequency is 1 Hz.

As an example, part of a time / sum frequency plot is given in Fig. 5.13. This plot corresponds with a weld of overall correct penetration, but also exhibits situations of overpenetration at \( t = 31, 36, 39, 45 \) and 48 s. Since the travel speed in the present case is 1.25 mm/s, these situations of overpenetration are located at a distance of 38.75, 45, 48.75, 56.25 and 60 mm from the beginning of the weld. Because these situations of overpenetration occur only during one pulse period at a time the overall weld penetration is not adversely affected.

The given example refers to a welding experiment in which use was made of extra current pulses. Analysis of the frequency is also possible in situations where the normal pulses are used for triggering the oscillations. However, as shown in the previous section, the signals obtained under these circumstances are often obscured by noise, which makes the frequency analysis less reliable.
Weld pool oscillation during pulsed GTA welding

Fig. 5.13  Plot of sum frequency versus time, corresponding with overall correct penetration and situations of overpenetration at t = 31, 36, 39, 45 and 48 s.
5.8 Conclusions

Based on the experiments described in the previous sections the following conclusions can be drawn.

- During pulsed current GTA welding three different situations can occur, depending on the welding conditions: underpenetration, correct penetration or overpenetration.
- The weld pool can be triggered into oscillation both during the pulse time and during the base time by the normal welding pulses. However, the amplitude of the oscillation triggered in this way is relatively small.
- Weld pool oscillations of larger amplitude can be obtained by applying extra current pulses, superimposed on the normal welding pulses at the beginning of the pulse time and at the beginning of the base time.
- The oscillation frequency of the weld pool can be calculated from the measured voltage variations, using an FFT algorithm.
- In the case of underpenetration, mode 1 oscillation occurs during both the pulse time and the base time. This situation is characterized by one (high frequency) peak in the frequency distribution.
- In the case of correct penetration, mode 3 oscillation occurs during the pulse time and mode 1 oscillation during the base time. This situation is characterized by two peaks in the frequency distribution (one high frequency peak and one low frequency peak).
- In the case of overpenetration, mode 3 oscillation occurs during both the pulse time and the base time. This situation is characterized by one (low frequency) peak in the frequency distribution.
- Sensing of weld pool geometry during pulsed current GTA welding is possible by monitoring the peaks in the frequency distribution. Correctly penetrated welds are obtained when two peaks appear in the frequency distribution.
- Deviations from correct penetration can be sensed within one pulse cycle, which corresponds with a time resolution of 1 s when the pulse frequency is 1 Hz.
Weld pool oscillation during pulsed GTA welding

References

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5.9 Q. Wang, Z. Geng and S. Qilong: “Real time full penetration control with arc sensor in the TIG welding of aluminium alloy”
Weld pool oscillation during GTA positional welding

chapter 6

Weld pool oscillation during GTA positional welding

6.1 Introduction

Positional welding is common practice in metal fabrication industry. It is applied in cases where manipulation of the workpiece to a horizontal (flat) position is impossible; it is of particular importance in the fabrication of pipes and tubular structures. The international (ASME) standard codes for positional welding are [6.1]:

- 1G (Fig. 6.1a): horizontal flat welding on horizontal workpiece;
- 2G (Fig. 6.1b): horizontal welding on vertical workpiece;
- 3G (Fig. 6.1c): vertical upward or downward welding on vertical workpiece;
- 4G (Fig. 6.1d): horizontal overhead welding on horizontal workpiece.

Orbital tube welding is a combination of 1G, 3G and 4G positional welding (and positions in between); the torch route is orbital around the pipe and the standard code is 5G when the pipe is horizontally fixed and 6G when it is fixed with an inclination. Orbital tube welding will be dealt with in chapter 9.
Weld pool oscillation during GTA positional welding

Fig. 6.1 Different welding positions: 1G (a), 2G (b), 3G upward (c1), 3G downward (c2) and 4G (d).

In Fig. 6.2 the forces acting on the weld pool for four different positions (1G, 2G, 3G and 4G) are schematically presented [6.2]. These forces are:

- \( F_g \) = gravity force, which is proportional with the pool mass;
- \( F_p \) = force due to the purging gas, which is proportional to the back surface area of the pool and the pressure of the gas;
- \( F_a \) = arc pressure force, which is proportional to the square of the arc current;
- \( F_s \) = surface tension force, which is dependent on the material composition and the temperature.
Weld pool oscillation during GTA positional welding

The resulting force determines in which direction the weld pool tends to flow, for example downwards in the case of a weld pool in the 3G position. In addition to the forces acting on the weld pool as a whole, there are also forces which act locally on the liquid metal in the weld pool. These forces give rise to fluid flow in the weld pool and are dealt with in section 2.4. Because welding is a dynamic process the viscosity of the liquid mass also plays a role in the flow behavior of the weld pool. Generally speaking, the resulting flow will be opposed by the viscosity. If this opposing action is maintained until solidification of the pool occurs, undesired pool flow will be minimized.

![Diagram of forces acting on weld pool in different positions](image)

**Fig. 6.2** Forces acting on the weld pool in different positions.

### 6.2 Weld pool behavior during positional welding

It may be expected that weld pool oscillation, as observed during welding in the flat position, will also occur during welding in non-flat positions. However, the oscillation frequency of the weld pool will be different in the various positions due to the role of the gravity force.

In Fig. 4.4 the relative error in the oscillation frequency, when neglecting the gravity force, is plotted as a function of the weld pool diameter for mode 1 oscillation and for
Weld pool oscillation during GTA positional welding

mode 2 oscillation. In the case of mode 1 oscillation this error is shown to be less than 1 % for a pool diameter smaller than 5 mm. The difference in oscillation frequency in the 1G position and in the 4G position (i.e. the maximum difference in oscillation frequency between two different positions) will therefore be less than 2 % (for the same pool diameter) and, hence, will be too small to be detected.

Figure 4.4 does not give a relative error for the mode 3 oscillation frequency when neglecting the gravity force; the membrane model does not contain a gravity term. To get an idea of the contribution of gravity, the approach of Maruo and Hirata [6.3] is evaluated (equation 4.16), taking for kD/2 the value 2.405 (the lowest order root of \( J_0 \)). Analogue to the approach, followed in section 4.3 the relative error for mode 3 oscillation can be calculated, which is about 5 % for a pool diameter of 5 mm and the maximum difference in oscillation frequency between the 1G and 4G position is 10 % for mode 3 oscillation. This is considerably larger than the error in the case of mode 1 oscillation, but still too small to be detected. For increasing pool diameter the decrease in frequency for the 1G position will be smaller than expected on basis of the increasing pool diameter; for the 4G position the decrease in frequency will be larger than expected on basis of the increasing pool diameter (the gravity term in equation (4.16) opposes the surface tension term).

Nevertheless, a problem may arise when welding in the 3G position and the gravity force tends to elongate the pool: the occurrence of the asymmetric mode 2 oscillation will become more probable in this position. Thus, it is necessary to take the precautions mentioned in chapters 4 and 5 to avoid mode 2 oscillation (low travel speed, small electrode diameter and electrode tip angle, short arc length and helium as shielding gas). Current pulsing is also an important tool in avoiding mode 2 oscillations because it results in a smaller average weld pool size.

A few remarks should be made about the influence of the welding direction on the shape and the dynamics of the weld pool. Evidently, the welding direction has no influence on the weld pool when welding in the 1G, 2G and 4G position, but it does have influence when welding in the 3G position (actually in every position between 1G and 4G). The two welding directions in the case of the 3G position are defined as:

- upward welding (3Gu): the weld pool tends to move away downward from the torch;
- downward welding (3Gd): the weld pool tends to move away downward towards the torch.
Weld pool oscillation during GTA positional welding

Fig. 6.3 Schematic illustration of positions of weld pool and arc for welding in position 3Gu (a) and 3Gd (b).

This implies that the direction of rotation of the tube has a significant influence on the shape of the weld pool and, hence, on the penetration. Downward welding is known to be the more difficult situation because the movement of the pool is forward (in the welding direction); during upward welding the movement of the pool is backward (opposite the welding direction).

Mathematical modeling of the weld pool in different positions by means of numerical analysis of heat flow was carried out by Ohji and Nishiguchi [6.4] and their results show a significant difference in weld pool shape between the 3Gu and the 3Gd positions, as displayed in Fig. 6.3. It can be seen in this figure that in the case of downward welding the pool squeezes between electrode and workpiece. As a consequence of this problems may occur which are specific for the 3Gd position. Most importantly, the arc will be obstructed in making contact with the unmelted workpiece material in front of the weld pool, resulting in a reduced process control and possible lack of fusion. Furthermore, the arc efficiency becomes lower because the heat is transported via the weld pool to the workpiece, instead of directly to the workpiece, which is the case when upward welding. Also the arc length becomes shorter, although this problem can be dealt with by applying AVC (Arc Voltage Control) instead of mechanical arc length control [6.5], as used in the present experiments.
Weld pool oscillation during GTA positional welding

An advantage of downward welding is the smaller risk for undercutting, as has been shown by Ohji and Nishiguchi [6.4]. The effect of forward and backward flow of the weld pool is well known in welding practice [6.6]. The typical turning points are known to be located at about 30° from backward movement to forward movement when upward welding and at about 210° from forward movement to backward movement when downward welding. In orbital welding therefore a weld pass is often divided in two upward steps: one from 150° to 30° clockwise and the other from 210° to -30° counterclockwise. This will be further discussed in chapter 9.

6.3 Experimental set-up

To investigate the oscillation behavior of the weld pool during pulsed GTA welding in non-flat positions, a multi-position welding unit was designed and constructed. The unit is illustrated in Fig. 6.4 and can be used for automatic welding of tubes of varying diameter (3-7 cm) and wall thickness in different positions. During welding the welding torch\(^1\) is kept in a fixed position, the electrode distance being fixed with the electrode distance positioner\(^2\), whereas the tube\(^3\) (workpiece) rotates. The required welding position is fixed with a position fixing unit\(^4\). In the figure the unit is set in the 3G position. By rotating the unit with respect to the supporting frame\(^5\) other positions can be realized: for instance, a rotation of 90° will result in the 4G position and a rotation of -90° results in the 1G position. The rotation of the tube is achieved with a DC electromotor\(^6\).

The rotation control unit\(^7\) is designed to measure the relative distance, the distance between the arc (weld pool) and the beginning of the weld. The unit generates 500 pulses/revolution, which implies that the accuracy in distance measurement is \((\pi/500)\times\text{tube diameter}\). The unit can also be used to measure the travel speed.
During welding the pulsed welding current, welding position, rotation speed, shielding gas flow rate and purging gas flow rate are dynamically controlled. This control system, partly based on commercial computer software and partly on home-built equipment, is schematically presented in Fig. 6.5.

In Fig. 6.6 a typical welding sequence is schematically presented. Arc ignition by means of HF is provided by the power source after receiving a start pulse from the control panel. The arc light sensor produces an output signal directly after receiving incoming arc light, i.e., at the moment of arc ignition. This output signal serves as a gate for the voltage and current reading, thereby protecting the registration unit from the harmful HF voltage. After the gate is set, the timing unit starts a count down before activating the rotation control unit. The count down duration is predefined and must be sufficiently long to form a weld pool of acceptable size. The stop of the rotation is triggered by the rotation control unit. The full rotation is usually a little more than $360^\circ$ (500 pulses) to achieve some weld overlap during which the current gradually decreases to zero.
Weld pool oscillation during GTA positional welding

Fig. 6.5 Control system of Multi Position Welding Unit.

After the arc light intensity has dropped below a certain level, the output signal of the arc light sensor switches off and the rotation will stop. Meanwhile, the arc voltage and arc current measurement are completed.
During welding the arc voltage is directly measured between electrode and workpiece, whereas the arc current is measured by means of a shunt. Galvanic shielding is provided by the welding monitor. The arc voltage signal passes a low pass filter before it is digitized. This is necessary for anti-aliasing during FFT analysis. The digitized voltage and current signals are transported by means of DMA (Direct Memory Access) to disk and meanwhile displayed on the PC monitor at a suitable refresh rate. Frequency analysis of the weld pool oscillation frequency during the complete welding run is carried out after termination of the weld. The position pulses, which are recorded together with the voltage and current signals, serve for distance calibration of the weld. Hence, the calculated frequencies can be plotted either on a time scale or on a distance scale, representing the entire weld. For frequency analysis the algorithm, described in chapter 5, is applied.
Weld pool oscillation during GTA positional welding

6.4 Results

Using the experimental set-up and the experimental procedure described above, welding experiments were carried out in the 1G, 2G, 3G and 4G positions with Fe 360 steel tubes having a diameter of 60 mm and a wall thickness of 3 mm and Fe 360 steel plates having a thickness of 3 mm. The welding conditions are summarized in Table 6.1, whereas the chemical composition of the materials is listed in Table 6.2. The average current was chosen in such a way that, due to the heat accumulation in the workpiece during welding, the weld pool geometry changed gradually from underpenetration via correct penetration to overpenetration so that the oscillation behavior of the weld pool during these transitions could be studied (in practical circumstances the average current and/or travel speed are adjusted during welding to compensate for this phenomenon).

![Graph](#)

**Fig. 6.7** Frequency spectra in the case of correct penetration in the 3Gd position.
Weld pool oscillation during GTA positional welding

The frequency spectra obtained are similar to those of Fig. 5.11a–c, except in the 3Gd position during correct penetration. In this position two frequency peaks appear in the frequency spectrum, both during the pulse time and during the base time (see Fig. 6.7). This deviating behavior is a consequence of the downward flow of the liquid weld metal, as explained in section 6.2: part of the liquid metal of the weld pool, created during previous pulse periods, squeezes between workpiece and torch. The frequency distribution, measured during the base time and the pulse time, has therefore components of the distribution, created in one or more earlier pulses.

By adding both spectra to one sum spectrum, this difference in oscillation behavior is camouflaged: the sum spectrum still shows two peaks during correct penetration, identical to the situations in other positions.

| workpiece material          | Fe 360 tube; diameter 60 mm, wall thickness 3 mm |
|                            | Fe 360 plate, 3 mm thickness                     |
| electrode material         | tungsten, 2% thoria                             |
| electrode diameter         | 2.4 mm                                          |
| electrode top angle        | 25°                                             |
| arc length                 | 2 mm                                            |
| shielding gas              | He, 24 l/min                                     |
| purging gas                | Ar, 3 l/min                                      |

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<th>3G u</th>
<th>3G d</th>
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<td>tube</td>
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Weld pool oscillation during GTA positional welding

In Figs. 6.8-6.12 the cumulative sum frequency spectra are given together with plots of the peak height versus time for the different welding positions. The cumulative frequency distribution is obtained by subsequently adding the frequency spectra measured at intervals of 5 s (Figs. 6.8, 6.9) or at intervals of 10 s (Figs. 6.10 - 6.12). In this way a maximum of information is incorporated in one graph; the use of 3D-graphs, which usually give poor information about exact values, is avoided. The figures show that in all cases a transition occurs from underpenetration via correct penetration to overpenetration: the mode 1 peak slowly decreases and the mode 3 peak slowly increases as a function of time; halfway, both peaks are at about the same height.

When considering the obtained results in more detail the following observations can be made:

- the transition (underpenetration > correct penetration > overpenetration) occurs in the case of the 1G and 2G positions on a smaller time scale than in the other positions; for the 1G position this can be explained by the smaller travel speed;
- the mode 1 and mode 3 peak frequencies slowly decrease as a function of time (especially in the 3G and 4G positions) due to the increasing weld pool size;
- there is no significant difference in oscillation frequency of the mode 1 and mode 3 oscillations for the different positions, which implies that gravity plays no role in oscillation behavior as predicted in section 6.2 (compare the 1G position with the 4G position);
- the 3Gd position shows slightly more scatter than the 3Gu position, which can be explained by the mode mixing, caused by the downward flow of the weld pool.

| Table 6.2 Chemical composition of the materials used (wt %) |
|----------------|--------|--------|--------|--------|--------|--------|--------|--------|
| workpiece     | C      | Si     | Mn     | P      | S      | O      | N      | Cr     | Ni     |
| tube          | 0.065  | 0.07   | 0.40   | 0.080  | 0.012  | 0.0170 | 0.070  | 0.06   | 0.065  |
| plate         | 0.094  | 0.04   | 0.54   | 0.017  | 0.009  | 0.0089 | 0.090  | 0.09   | 0.040  |

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Fig. 6.8 Cumulative sum frequency spectrum (a) and plot of peak height versus time for the transition from underpenetration via correct penetration to overpenetration in the case of the 1G position.
Weld pool oscillation during GTA positional welding

Fig. 6.9 Cumulative sum frequency spectrum (a) and plot of peak height versus time for the transition from underpenetration via correct penetration to overpenetration in the case of the 2G position.
Weld pool oscillation during GTA positional welding

![Graph](image)

**Fig. 6.10** Cumulative sum frequency spectrum (a) and plot of peak height versus time for the transition from underpenetration via correct penetration to overpenetration in the case of the 3Gv position.
Weld pool oscillation during GTA positional welding

Fig. 6.11 Cumulative sum frequency spectrum (a) and plot of peak height versus time for the transition from underpenetration via correct penetration to overpenetration in the case of the 3Gd position.
Weld pool oscillation during GTA positional welding

Fig. 6.12 Cumulative sum frequency spectrum (a) and plot of peak height versus time for the transition from underpenetration via correct penetration to overpenetration in the case of the 4G position.
Weld pool oscillation during GTA positional welding

6.5 Conclusions

Based on the experimental results obtained, the following conclusions about weld pool oscillation during welding in non-flat positions can be drawn.

- There is no significant difference in oscillation behavior for both the mode 1 and mode 3 oscillations between the flat position and each of the non-flat positions.
- For each welding position it is possible to detect the transition between underpenetration and correct penetration and the transition between correct penetration and overpenetration by means of frequency mode analysis.
- In the case of the 3Gd position, transition detection can be problematic because of the disturbing downward movement of the weld pool.
Weld pool oscillation during GTA positional welding

References


Weld pool oscillation during GTA welding with cold wire supply

Chapter 7

Weld pool oscillation during GTA welding with cold wire supply

7.1 Introduction

GTA welding with cold wire supply [7.1] is an extension of normal GTA welding. The characteristic feature of the process is that cold wire is added to the weld pool as a consumable during the welding process. The term "cold wire" is chosen to distinguish the process from GTA welding with hot wire supply. During welding with hot wire supply the wire is brought to a higher temperature by means of resistance heating in order to increase the melting rate. GTA welding with cold wire supply can be considered as a link between normal GTA welding and GMA welding with the advantages of both processes. However, some of the complexity inherent to GMA welding is also characteristic for GTA welding with cold wire supply.

Although mainly applied for filling passes, the process can also be used for root pass welding, the advantages being an increase in productivity but, more importantly, a smaller demand on seam preparation. For instance, in the case of GTA welding with cold wire supply, root pass welding is possible with a root gap of more than 1 mm in the case of a 3 mm plate thickness.
Weld pool oscillation during GTA welding with cold wire supply

It was shown in chapters 5 and 6 that during normal GTA welding both in flat and in non-flat positions, the weld pool can be triggered into oscillation and that the oscillation frequency can be extracted from the arc voltage variation by means of FFT analysis.

It should be expected that the weld pool will behave in a similar way in the case of GTA welding with cold wire supply and that oscillation will occur either in mode 1 or in mode 3, depending on the pool geometry as long as the material supply does not alter this geometry too drastically.

Under normal conditions the wire is inserted at a constant feed rate into the weld pool. Due to the supply of the cold material, the pool temperature will be lower than when welding was performed without wire supply. In the case of pulsed current welding the weld pool size decreases during the base time and increases again during the pulse time. Due to the changing weld pool size there is a certain risk that the wire freezes into the solidifying weld bead.

In the flat position the wire diameter and the wire feed rate can be chosen at such values that the wire does not stick into the pool, but melts to droplets which fall into the pool in order to avoid the risk of freezing. Unfortunately, when welding in non-flat positions this practice can not be applied and the wire should be applied directly to the weld pool.

A phenomenon which might affect the weld pool oscillation when GTA welding with cold wire supply, is the impact of transferring droplets on the weld pool, thereby disturbing the pool surface. This surface disturbance causes a decrease of the signal to noise ratio. Especially mode 1 oscillations will be sensitive to this effect, because these oscillations are in fact surface waves. Mode 3 oscillations are volume oscillations and are therefore expected to be less sensitive to droplet impact.

Because the mass of the pool increases when a droplet strikes the pool, the oscillation frequency is expected to decrease. In view of this, droplet transfer might result in variations in oscillation frequency.

Apart from the impact of droplets, also the change in weld pool temperature caused by incoming droplets might affect the oscillation behavior of the weld pool. This effect also will be a cause of variation in oscillation frequency.
Weld pool oscillation during GTA welding with cold wire supply

Experiments were carried out with the aim:

- to find out whether weld pool oscillations, as observed during pulsed GTA welding both in flat positions and in non-flat positions, will also occur during pulsed GTA welding with cold wire supply;
- to determine the influence of cold wire supply (particularly the effect of droplet transfer) on the oscillation behavior;
- to evaluate the possibilities of sensing the transitions from underpenetration to correct penetration and from correct penetration to overpenetration by means of oscillation frequency analysis in the case of pulsed GTA welding with cold wire supply.

7.2 Experimental conditions

The set-up used for the experiments consists essentially of a pulsed GTA welding machine, equipped with a cold wire supply unit. In this set-up the wire is supplied by the wire feed unit with a constant wire feed speed. The end of the wire is directed towards the weld pool by means of a mouthpiece (a GMAW contact tube). The situation is schematically presented in Fig. 7.1. For measurement and control use was made of the unit shown in Fig. 6.5. The wire supply rate was matched with the travel speed.

![Diagram](image)

Fig. 7.1 Part of the experimental set-up used for pulsed GTA welding with cold wire supply.
Weld pool oscillation during GTA welding with cold wire supply

Fig. 7.2  Schematic illustration of the V-type groove used for the experiments.

Pulsed current welding was carried out in flat position using Fe 360 steel plates of 5 mm thickness, prepared with V-type grooves of 90° (see Fig. 7.2) and SG2 welding wire of 1 mm diameter. The chemical composition of the materials is listed in Table 7.1. The welding conditions used are listed in Table 7.2.

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<td>0.0084</td>
<td>-</td>
<td>0.022</td>
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</table>

The effective welding current was chosen to be sufficiently high to melt both the wire at the feed rate used and part of the workpiece.

A pulse time of 20 % of the total cycle time was found to be sufficiently large to obtain full penetration in the situation without wire supply. With cold wire supply the weld cools too rapidly to achieve full penetration with 20 % pulse time; 30 % was necessary for full penetration. For overpenetration 40 % pulse time was found to be required. The welding sequence followed was taken to be identical to that shown in Fig. 6.5.
Weld pool oscillation during GTA welding with cold wire supply

Table 7.2 Welding conditions for experiments with cold wire supply

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</tr>
<tr>
<td>trigger time (ms)</td>
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</table>

7.3 Results

To examine the influence of cold wire supply on the oscillation behavior of the weld pool, a number of welding experiments, with or without cold wire supply, was carried out using the set-up and following the procedure described in the previous section. Some of the results are shown in Figs. 7.3 - 7.6.

Figure 7.3 shows a time sample of 1 s of the arc voltage and arc current recorded during welding without wire supply under optimal (correct penetration) conditions, using a pulse time of 20%. The figure shows that correct penetration occurs with mode 3 oscillation of about 40 Hz during the pulse time \( t_p \) and mode 1 oscillation of about 80 Hz during the base time \( t_b \).

In Fig. 7.4 a typical time sample is given recorded during welding with cold wire supply under optimal (correct penetration) conditions, using a pulse time of 30% and a wire
Weld pool oscillation during GTA welding with cold wire supply

supply at a rate of 5.5 mm/s (= 34 mg/s). The oscillation frequencies are about 40 Hz during \( t_p \) (mode 3) and 90 Hz during \( t_o \) (mode 1). The disturbances in the voltage signal at \( t \approx 0.65 \) s and \( t \approx 0.80 \) s are presumably caused by droplet impact in the weld pool.

![Current and Voltage Graph](image)

**Fig. 7.3** Time sample of arc voltage and arc current recorded during pulsed GTA welding without wire supply under correct penetration conditions.

![Current and Voltage Graph](image)

**Fig. 7.4** Time sample of arc voltage and arc current recorded during pulsed GTA welding with cold wire supply under correct penetration conditions, showing droplet disturbance at \( t \approx 0.65 \) s and at \( t \approx 0.80 \) s.
Weld pool oscillation during GTA welding with cold wire supply

Fig. 7.5  Time sample of arc voltage and arc current recorded during pulsed GTA welding with cold wire supply under correct penetration conditions, showing droplet disturbance at $t \approx 0.85$ s.

Fig. 7.6  Time sample of arc voltage and arc current recorded during pulsed GTA welding with cold wire supply under overpenetration conditions, showing droplet disturbance at $t \approx 0.65$ s.

Incidentally a droplet strikes the surface of the weld pool at an impact sufficiently large to trigger the pool into oscillation. This phenomena can be observed in Fig. 7.5 where a droplet strikes the weld pool at $t \approx 0.85$ s. The oscillation frequency is about 110 Hz.
Weld pool oscillation during GTA welding with cold wire supply

before droplet impact and about 80 Hz, directly following droplet impact. The observed
decrease in oscillation frequency (from 110 to 80 Hz) corresponds with the increase of
the pool size caused by the droplet transfer to the weld pool (an effect which is enhanced
by the V-shape of the groove).
It should be noted that the effect of droplet impact as described in the foregoing refers
specifically to mode 1 oscillation. The influence of droplet impact on mode 3 oscillation
is negligibly small, as can be seen in Fig. 7.6 where a droplet strikes the surface of the
weld pool at $t \approx 0.65$ s.
Another effect of droplet transfer is the temperature change of the weld pool, resulting in
a change in surface tension and liquid density [7.2], which in turn gives rise to a change
in oscillation frequency. This change in oscillation frequency is proportional to $\sqrt{Y/\rho}$
(see section 4.2). Hence, the measured oscillation frequency is characterized by
considerable scatter. This scatter brings the mode 1 frequency range closer towards the
mode 3 frequency range, which evidently is not advantageous for frequency mode
analysis.

Some experiments were carried out to examine the weld pool oscillation behavior during
the transition from underpenetration to correct penetration and from correct penetration to
overpenetration. A typical example of the results obtained is presented in Fig. 7.7, in the
form of cumulative sum frequency spectra (time intervals of 5 s), as defined in section
6.4.
The results show that also in the case of pulsed GTA welding with cold wire supply it is
possible to detect the transitions from underpenetration to correct penetration and from
correct penetration to overpenetration by monitoring the oscillation frequency of the weld
pool.
Fig. 7.7 Cumulative sum frequency spectrum (a) and plot of peak height versus time (b) for the transition from underpenetration via correct penetration to overpenetration in the case of welding with cold wire supply.
7.4 Weld pool oscillation during GMA welding

In the previous section attention was given to the influence of droplet transfer on the oscillation behavior of the weld pool in the case of pulsed GTA welding with cold wire supply. The fact that droplet impact can generate oscillation under these conditions as indicated in Fig. 7.5 suggests that droplet transfer can also generate weld pool oscillation during Gas Metal Arc (GMA) welding.

In the case of GMA welding [7.3] the arc burns between a fusible electrode and the workpiece to be welded. The electrode consists of either a solid or a flux-cored wire, which is fed into the arc at a rate equal to the melt-off rate.

Transport of molten metal from the electrode to the weld pool takes place in the form of droplets (open arc welding) or by means of short-circuits (short-circuiting welding). The material transfer for both situations is schematically shown in Figs. 7.8a and b, respectively. It may be expected that in both modes of GMA welding the weld pool can be triggered into oscillation, either by droplet impact or by disruption of the short-circuits and re-ignition of the arc. Although indirect evidence of the existence of weld pool oscillation has been given in the case of short-circuiting GMA welding [7.4, 7.5], direct observation of oscillation, neither in the case of open arc welding nor in the case of short-circuiting welding has been reported. Apparently, weld pool oscillation during GMA welding is obscured by other effects, inherent to this process.

At this point it must be noted that, under normal welding conditions, droplet transport in the case of open arc welding occurs at frequencies of 200 - 400 Hz and that short-circuiting in the case of short-circuiting welding occurs at frequencies of 100 - 200 Hz. It must therefore be expected that the frequency spectrum will be dominated by either the droplet transfer frequency or the short-circuiting frequency.
7.5 Conclusions

On the basis of the experimental results obtained, it can be concluded that weld penetration sensing by means of oscillation frequency analysis is possible during pulsed GTA welding with cold wire supply. However, it must be realized that the frequency analysis leads to results which are less accurate than those obtained in the case of pulsed GTA welding without wire supply, due to the effect of droplet transfer on the size and temperature of the weld pool.
Weld pool oscillation during GTA welding with cold wire supply

References

Design of a feedback system for penetration control based on oscillation mode analysis

chapter 8

Design of a feedback system for penetration control based on oscillation mode analysis

8.1 Introduction

In the previous chapters attention was given to weld pool oscillation during GTA welding and in particular to the possibility of using weld pool oscillation as a tool for sensing weld penetration. It was shown that penetration sensing is indeed possible by measuring the oscillation frequency continuously during the welding process.

This approach is of specific interest when use is made of pulsed welding current. In that case correct penetration is characterized by the presence of two distinct frequency peaks in the frequency distribution (a high frequency peak, corresponding to mode 1 oscillation during the base time and a low frequency peak, corresponding to mode 3 oscillation during the pulse time). Deviations from correct penetration result in one peak in the frequency distribution (a high frequency peak in the case of underpenetration or a low frequency peak in the case of overpenetration). It was also found that generally speaking the oscillation behavior is not adversely affected by the welding position or by cold wire supply.
Design of a feedback system for penetration control based on oscillation mode analysis

Although the frequency information obtained by sensing can be directly used for off-line quality control, it is of more interest to use this information for direct corrective actions. A logical next step is therefore the development of a feedback system. Such a system should ultimately result in the possibility of real-time in-process penetration control (IPPC).

With respect to the development of a feedback system the following remarks should be made:

- corrective actions following feedback of sensed data involve changing the heat input; this can be accomplished by changing the welding current or by changing the travel speed;
- changing the travel speed can have a negative influence on oscillation behavior (mode 2 oscillation at large travel speed), therefore feedback based on changing the welding current is the safest option;
- the computer program, written for generating current pulses, was can easily be featured with a possibility to adjust the welding current during welding;
- the arc voltage and arc current are digitally recorded with the same computer program and stored on disk for off-line frequency analysis with a dedicated frequency analysis program;
- a combination of the two programs in one IPPC welding program is possible with the computer speed on most of the present day computers;
- the described computer program can easily be supplied with a so-called quality control unit, which can produce a printout of the oscillation modes as a function of the welding time (distance from the beginning of the welding run);
- the described computer program automatically generates a current program (pulse parameters as function of the welding time) which can be used in the next welding program: the program is self-learning.

The last point can be very time saving: for correct penetration a current program has to be developed for every possible situation (material, dimensions, position, travel speed etc.) when welding without feedback control.

An additional remark must be made concerning the negative influence on oscillation behavior when changing the travel speed (second point). This negative influence can be avoided by welding with zero travel speed. This can be accomplished when welding and
Design of a feedback system for penetration control based on oscillation mode analysis

traveling are decoupled. This is called spot welding and will be dealt with separately in section 8.4.

In the case of welding with feedback control the start current has to be chosen somewhere in the range of the average welding current for correct penetration of the applied material; a well functioning feedback program will then tune the pulse parameters for correct penetration along the entire weld.

In the following a description is given of a feedback system for in-process control of weld penetration in the form of a concept version of an IPPC welding program. Some attention is also given to spot welding, an alternative approach to in-process penetration control.

8.2 Design of a feedback system

As has been outlined in the introduction, the basic features of a well functioning feedback system are defined by successfully operating stand-alone functions; a description of the separate functions is given below.

Programming is carried out with LabVIEW, a dedicated data acquisition program, developed by National Instruments [8.1]. Data acquisition and control signals operate via an internal PC-board (LabPC+) developed by the same supplier. To achieve galvanic protection for the computer hardware, the data and control signals pass through opto-coupling elements, designed and home-built for this purpose. The situation is schematically shown in Fig. 8.1.

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Design of a feedback system for penetration control based on oscillation mode analysis

![Diagram](image)

Fig. 8.1 Schematic illustration of measurement and control system with galvanic shielding in the interface for digital and analog input/output (I/O).

8.2.1 Pulse parameter control

It was shown in sections 5.5 and 5.6 that the best way to trigger oscillations in the weld pool is to make use of extra triggering pulses. In view of this, triggering was carried out by means of computer controlled pulse generation, which is a flexible technique for generating pulses of any desired shape.

The current pulse control is based on a wave generator: a software tool for generating wave functions on the analog output channels of the LabPC+ board (AO wave [8.2]), which can be fed with various basic input waves like sinusoidal, triangular or rectangular waves. The wave output is connected to an opto-coupling interface (with amplification factor $\beta$) to achieve galvanic shielding before the connection to the power source. The output wave is continuously generated (like a function generator) unless the input wave function is modified. There is no phase shift between the old and the new wave function after modification.

The time resolution of the output wave is:

$$\Delta t = \frac{1}{FN}$$  \hspace{1cm} (8.1)
Design of a feedback system for penetration control based on oscillation mode analysis

with \( F \) the pulse frequency and \( N \) the number of points; the amplitude resolution is: \( 10/4096 \, \text{V} = 2.4 \, \text{mV} \) (12 bit on a scale of 10 V). The power source used (inverter type ELMA) has a maximum output current of 300 A, corresponding with 3 V input. Hence, with \( \beta = 0.3 \) the current resolution is \( 300/4096 \, \text{A} = 73 \, \text{mA} \), which is far below the detection limit. To achieve a rise time for the current pulses smaller than 1 ms, \( N \) must be larger than \( 1000/F \). To discount for a phase shift in the interface and the power source, \( N \) is set at \( 4000/F \).

Figure 8.2 shows a schematic representation of the wave generation during the \( n^{\text{th}} \) pulse cycle. In order to save computer time, a new wave function is only generated in case of a change: in each cycle the \( n^{\text{th}} \) wave function is compared to the \( n-1^{\text{th}} \) wave function; only when these two differ, the wave generator is fed with a new input wave. Changes in the \( n^{\text{th}} \) cycle, therefore, will only affect the wave in the \( n+1^{\text{th}} \) cycle.

Fig. 8.2    Schematic illustration of wave generation for current control during the \( n^{\text{th}} \) cycle.
8.2.2 Current and voltage measurement

The function on which the current and voltage measurements are based (AI wave) is equivalent to the output function (AO wave), described in the previous section. Once the function is fed with its initializations, it acts rather autonomously (Fig. 8.3): it samples the analog input channels with a given sample frequency (S) and puts the retrieved data via a FIFO buffer at its output in blocks of M samples. To preclude the occurrence of a phase shift between input and output, the block size is defined by the pulse frequency and the sample frequency: $M = S/F$ (only one block is retrieved during each pulse cycle).

---

**Fig. 8.3** Schematic illustration of sample sequence of arc voltage and arc current during the $n^{th}$ cycle.
Design of a feedback system for penetration control based on oscillation mode analysis

The output is buffered in order to give the computer the opportunity to carry out its other tasks (the output buffer as well as the input buffer must be as small as possible in order to minimize the time shift between “action” and “reaction”). Meanwhile, the sampled data is written to disk by means of DMA (Direct Memory Access) and monitored on the user interface. A description of the interface and anti-aliasing filter has been given in chapter 6.

8.2.3 Frequency analysis

Frequency measurement is based on FFT (Fast Fourier Transform) analysis, one of the fastest algorithms known for frequency analysis [8.3]. Its restriction is that analysis can only be performed if the number of time samples is a power of 2. The number of voltage samples (m) is therefore 32, 64, 128, 256 etc, depending on the frequency resolution that is demanded, which can be expressed as:

\[ \Delta f = \frac{S}{m} \]  \hspace{1cm} (8.2)

The sample frequency is limited by the Nyquist frequency \( f_{\text{Nyq}} = \frac{S}{2} \), the highest frequency which can be detected [8.4].
Design of a feedback system for penetration control based on oscillation mode analysis

Fig. 8.4 Schematic illustration of set-up for frequency analysis during the n^th cycle.
Design of a feedback system for penetration control based on oscillation mode analysis

In Fig. 8.4 the frequency analysis program is schematically presented. The peak detector reveals the trigger peaks in the welding current. With a delay of $\Delta t_p$ and $\Delta t_b$ a number of m samples is extracted from the arc voltage, recorded during the pulse time and base time, respectively. After extraction, the signal is windowed and filtered: the signal is split in two branches and passes a bandfilter in each branch, the center frequency of which is set at the expected mode 1 frequency and mode 3 frequency and the bandwidth at a suitable value to allow some frequency variation. Windowing is necessary to smooth the naturally truncated signal (the discontinuities at the beginning and the end of a truncated signal cause high frequency leaks, which might give false spectral information). The frequency spectrum after FFT analysis consists of m/2 points (from $\Delta f$, spaced $\Delta f$ to $f_{Nyq}$). Thus, each pulse cycle results in a frequency distribution for both the pulse time and the base time, suitable for further analysis.

8.2.4 Feedback control based on frequency analysis

The procedure for sensing correct penetration, which is outlined in chapter 5, forms the basis of the feedback control system developed. As a consequence of filtering, using bandpass-filters with center frequencies equal to the mode 1 and mode 3 natural oscillation frequencies, the frequency distribution always shows two peaks. In case of correct penetration the frequency distributions during the pulse time and during the base time generally have the shape of curves a and b in Fig. 8.5, respectively. The solid curve a shows the frequency distribution during the pulse time and the dashed curve b shows the frequency distribution during the base time. In case of underpenetration these curves take the form of curves c and d and in case of overpenetration they take the form of curves e and f.

The change from curve a to curve c is an indication of the development of underpenetration: the mode 1 peak during the pulse time has risen at the expense of the mode 3 peak; the change from curve b to curve f is an indication of the development of overpenetration: the mode 3 peak during the base time has risen at the expense of the mode 1 peak.
Design of a feedback system for penetration control based on oscillation mode analysis

The essential element of feedback control is that the transition from curve a to curve c and from curve b to curve f must activate a trigger for a current modification. When \( P_3 \) and \( P_1 \) are defined as the heights of the mode 3 peak and the mode 1 peak during the pulse time, then the current must increase (\( I_{n+1} = I_n + \Delta I \)) when \( P_3 < C P_1 \), where \( C \) is a tuning factor, which usually has a value of about 1. In a similar way the current must decrease (\( I_{n+1} = I_n - \Delta I \)) when \( B_3 > C B_1 \), with \( B_3 \) and \( B_1 \) the heights of the mode 3 peak and the mode 1 peak during the base time.

![Frequency spectrum](image)

Fig. 8.5  Frequency spectrum during the pulse time (solid line) and during the base time (dashed line) from left to right for correct penetration, underpenetration and overpenetration.

The tuning factor \( C \) gives the operator the opportunity to influence the appearance of the weld. Generally speaking: if \( C \) is larger than 1, the weld pool is large and there is a tendency for overpenetration; if \( C \) is smaller than 1, the pool is small, with a greater risk of underpenetration. A small tuning factor demands a large effort as far as weld seam preparation (machining and cleaning) is concerned, while a large tuning factor requires less weld seam preparation. The current step \( \Delta I \) determines the speed of the corrective action and must be tuned with the travel speed (larger at larger travel speed).
Design of a feedback system for penetration control based on oscillation mode analysis

8.3 The feedback system incorporated in a fully automatic welding unit

The combination of the basic elements of the welding system (pulse parameter control, current and voltage measurement, frequency analysis and feedback control) results in a fully automatic welding unit, which can be used for penetration control. The procedure followed is schematically presented in Fig. 8.6. The figure shows the various actions which are taken by the system during the \( n \)th pulse:

- the current is adjusted in case this was decided as a result of the frequency mode analysis in the \( n-1 \)th cycle;
- the arc voltage variation is sampled, extracted and analyzed, resulting in two frequency distributions (one for the pulse time and one for the base time);
- a decision is made about a possible current adjustment in the \( n+1 \)th cycle on basis of comparison of the mode 1 and mode 3 peaks (both during the pulse time and during the base time) using a tuning factor, adjusted by the operator;
- the user interface is updated and modifications, made by the operator, are applied and, if possible, carried out in the \( n+1 \)th cycle.

The user interface shows time samples of the arc current and the arc voltage, together with the corresponding frequency plots. This gives the operator the opportunity to intervene into the process if necessary by making current adjustments, independent of the feedback procedure. An example of the information exhibited by the user interface is displayed in Fig. 8.7.

Usually, the process adjustments take place in the form of pulse current modifications. However, it is also possible to adjust the base current or the pulse time.

Before welding, the program passes through an initialization cycle during which:

- the current program is loaded;
- the shielding gas type is chosen;
- the window and filters (center frequencies and bandwidth) are adjusted;
- the noise level is measured to estimate an offset level;
- the warming-up period (the period of stationary arc burning during which the weld pool is formed) is adjusted.
Design of a feedback system for penetration control based on oscillation mode analysis

![Diagram of IPPC feedback system](image)

Fig. 8.6 Schematic illustration of IPPC feedback system, showing sampling, analysis, decision taking and current control during the nth cycle.

After welding is completed the current is put in a down-slope (the current decreases from its actual value to zero value over a period of several seconds) and after extinction of the arc, a post welding gas flow is maintained for a few seconds to prevent the electrode from oxidizing while still hot. Finally, the current program is stored on disk and can be used as welding program for future welds.

The program can also be run again in the playback mode: in this mode arc voltage and arc current are not measured, but read from the disk on which the recorded data was written. This gives the opportunity to repeat the frequency analysis (for example, to examine other filter parameters which might accommodate the feedback procedure in a better way).
8.4 Spot welding

In the previous sections a system for in-process sensing and control of weld penetration was described, which is based on feedback of oscillation frequency data monitored during welding. In this system the welding torch moves with constant travel speed along the weld seam and corrective actions are taken by changing the welding current (pulse current).

An alternative approach to in-process control of penetration is spot welding. In spot welding a continuous array of equi-spaced, partly overlapping spot welds is formed and this is realized by moving the welding torch stepwise along the weld seam. Welding is carried out under static conditions (zero travel speed) and is continued until full
Design of a feedback system for penetration control based on oscillation mode analysis

penetration is achieved, after which the torch moves on with high travel speed to the next position. This procedure is schematically illustrated in Fig. 8.8.

Although welding can be performed with constant current, trigger pulses are needed to generate oscillations and to trigger the control program for analysis. As algorithm a simplified version of the one described in sections 8.2 and 8.3 can be used: when full penetration is achieved, the oscillation mode turns from mode 1 to mode 3; this gives the signal that the spot weld is completed and the torch travels to the next spot, after which the entire cycle is repeated. The algorithm is schematically presented in Fig. 8.9. The decisive variable in the spot welding process is the welding time per spot which, due to accumulation of heat, will gradually decrease while the process is proceeding. The degree of penetration: heavy (secure) or light (risky) can be adjusted by the sensitivity. This is illustrated in Fig. 8.10 in which the sensitivity passes from high (a) via medium (b) to small (c). It is clear that the overlap between the subsequent spot welds must be large when the sensitivity is high and can be smaller when the sensitivity is small (compare Fig. 8.11a with Fig. 8.11b).

![Spotwelds Diagram](image)

**Fig. 8.8** Schematic presentation of a spot welding sequence, showing the partly overlapping spot welds, the travel speed and the penetration as a function of time.
Design of a feedback system for penetration control based on oscillation mode analysis

Fig. 8.9  Control algorithm for spot welding.

Fig. 8.10  Different sensitivities for spot welding: high (a), medium (b) and small (c).

To test the possibilities and limitations of the spot welding feedback system, a number of preliminary experiments was carried out. It was found that the system can be used successfully for penetration control in single pass welding. However, application of the system has a number of disadvantages in comparison with the system described in the previous sections:

- the weld bead appearance produced is rather course and irregular;
- the transition from partial to full penetration occurs rather abruptly, which makes a fine control of the bead width at the underside somewhat problematic;
- the arc efficiency is low because the arc overheats the liquid metal in the weld pool, instead of continuously melting solid material.
Design of a feedback system for penetration control based on oscillation mode analysis

In view of these limitations it was decided to not further pursue the spot welding approach, but to carry out further experiments with the system, described in sections 8.2 and 8.3.

Fig. 8.11 Difference in spot weld overlap for different sensitivity: large overlap in the case of a light sensitivity (a) and small overlap in the case of a small sensitivity.

8.5 Conclusions

In this chapter a description is given of the first version of a feedback system for in-process weld penetration sensing and control based on oscillation mode analysis. The system consists of a unit to generate a pulsed welding current, a unit to sample arc voltage and arc current variations, a unit for oscillation frequency analysis and a unit for current adjustment, based on oscillation mode analysis, to maintain correct penetration. In this system most of the parameters can be defined by the operator, but may in a future version of the program be constant. For example, optimal values for the filter parameters can be kept constant once they are estimated for a particular situation.

The system can be equipped with special facilities and adjustments for orbital welding, which will be dealt with in the next chapter.

Attention was also given to spot welding, an alternative approach to in-process control of penetration. However, this approach was not further pursued in view of a number of apparent limitations.
Design of a feedback system for penetration control based on oscillation mode analysis

References

8.2 LabVIEW Reference Manual Data Acquisition VI (1994), National Instruments Corporation, 6504 Bridgepoint Parkway, Austin Texas
chapter 9

Orbital tube welding with feedback control based on frequency mode analysis

9.1 Introduction

In the previous chapter a detailed description was given of the principles and the design of a feedback system for in-process weld penetration control (IPPC).

This chapter deals with the implementation of this system for orbital tube welding [9.1]. With this purpose the feedback system was incorporated in a control program for an orbital welding unit. The total set-up was designed to be able to complete orbital welds in one pass, independent of the start position; at any time the program must be capable to adjust the current for correct penetration in each position.

In the following sections attention will subsequently be given to: the experimental set-up, the selection of the most suitable program parameters, calibration experiments carried out with the system, applications of the system for in-process penetration control under different conditions and applications of the system, in which situations with feedback are compared to situations without feedback.
9.2 Experimental set-up

The welding experiments were carried out with the orbital tube welding unit, schematically shown in Fig. 9.1. The unit consists of a DC electromotor\(^1\) which drives the orbital rotation via a transmission unit\(^2\). The tube\(^3\) to be welded is centered with three tube fix screws\(^4\). The GTA welding torch\(^5\) is fixed to the gear wheel\(^6\) for the orbital rotation and is centered above the seam with the seam fix screw\(^7\); the torch is provided with mechanical arc length control\(^8\). The electrode-tube distance is fixed with the electrode fix screw\(^9\). The control system is identical to that described in chapter 6.

Fig. 9.1 Schematic set-up of orbital welding unit with: 1 = motor, 2 = transmission unit, 3 = tube, 4 = tube fix, 5 = torch, 6 = gear wheel, 7 = seam fix, 8 = arc length control, 9 = electrode distance fix.

For the experiments tubes of unalloyed steel (Fe 360) and stainless steel (AISI 304) of different size and wall thickness were used. The chemical composition of the tube materials is given in Table 9.1.
Orbital tube welding with feedback control based on frequency mode analysis

Table 9.1 Chemical composition of the tube materials used (wt %)

<table>
<thead>
<tr>
<th>steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>O</th>
<th>N</th>
<th>Cr</th>
<th>Ni</th>
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<td>0.055</td>
<td>0.008</td>
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<td>0.030</td>
<td>0.020</td>
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<td>0.080</td>
<td>0.012</td>
<td>0.017</td>
<td>0.070</td>
<td>0.060</td>
<td>0.065</td>
</tr>
<tr>
<td>AISI 304</td>
<td>0.065</td>
<td>0.28</td>
<td>1.83</td>
<td>0.029</td>
<td>0.017</td>
<td>0.015</td>
<td>0.024</td>
<td>18.02</td>
<td>9.590</td>
</tr>
</tbody>
</table>

9.3 Selection of the program parameters

In addition to the pulse parameters (pulse current \(I_p\), base current \(I_b\), pulse time \(t_p\), base time \(t_b\), trigger current \(I_t\) and trigger time \(t_t\)) the program parameters also comprise the travel speed \(v\), the frequency resolution \(\Delta f\) and the sample frequency \(S\). The program parameters have to be chosen in such a way that current control is possible over a wide range of current values to prevent the control from reaching its limits. As control parameter either the pulse current or the pulse time can be used. The base current is not suitable as control parameter, due to its small value. In fact, the base current is used for arc maintenance.

For a motivated selection of the program parameters the following considerations should be taken into account.

1. The sample frequency must be chosen, according to the sample theorem [9.2], at 1000 Hz or larger.
2. The frequency resolution must be better than 10 Hz.
3. For reasons explained in chapters 4 and 5, the travel speed should lie between 0.5 and 2 mm/s.
4. For reliable penetration the overlap of the spot welds at the underside of the weld must be at least 50 %.
5. The maximum thickness of the seam is 3 mm (either 3 mm wall thickness for an I-groove or 3 mm root thickness for a V-groove). Hence, the weld pool diameter at the underside must be at least 3.6 mm to guarantee the occurrence of mode 3 oscillation [9.3].
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6. In cases where more than one set of program parameters satisfy the demands, the set which requires the shortest computer time must be chosen.

7. The minimum value of the base current must be about 20 A; below that value the arc becomes unstable due to rapidly moving anode spots, resulting in a voltage variation which overrules the voltage variation due to weld pool oscillations.

8. The maximum value of the pulse current must be about 140 A; above that value the arc pressure becomes too large and oscillations are damped out immediately.

According to the requirements formulated in points 4 and 5 the maximum displacement during one pulse period should be 1.8 mm and the relation between the pulse frequency and the travel speed (mm/s) therefore becomes:

\[
\frac{V}{F} < 1.8
\]

(9.1)

With reference to point 2 a frequency resolution of about 8 Hz can be reached when \( S/m = 500/64, 1000/128, 2000/256 \) etc. (see chapter 8). Because the computer time necessary for FFT analysis is proportional to \( m\sqrt{m} \) [9.4], the sample frequency is set at 1000 Hz, which is the most economical setting in agreement with points 1 and 6. The number of voltage samples to be extracted both during the pulse time and during the base time is therefore 128, which corresponds with 128 ms when \( S = 1000 \) Hz.

Furthermore, the weld pool needs a certain time to recover from the sudden change in arc pressure (arc current) at the beginning of the pulse time and the base time; the absolute minimum of both the pulse time and the base time is therefore 200 ms. This is 20 % of the total cycle time at a pulse frequency of 1 Hz, 40 % at a pulse frequency of 2 Hz etc. However, the maximum pulse time is limited to about 50 % in order to maintain the advantages of pulsed welding compared to constant current welding (chapter 5). In view of this, it is clear that when the pulse frequency is selected at 1 Hz, a maximum freedom in the choice of the pulse time is retained. This selection is also in agreement with point 6; according to equation (9.1) the maximum travel speed is now 1.8 mm/s which is in good agreement with point 3.

At this point the selection of the control parameter must be motivated. As stated above both the pulse time and the pulse current can be used as control parameter and a choice
Orbital tube welding with feedback control based on frequency mode analysis

must be based on the criterion of a maximum relative variation of the energy input (ΔQ/Q).

In the case of control by means of the pulse time, ΔQ/Q is:

\[
\frac{\Delta Q}{Q} = \frac{I_p t_{p_{\text{max}}} - I_p t_{p_{\text{min}}}}{I_p t_{p_{\text{max}}} + I_p t_{p_{\text{min}}}} \times 100\% = \frac{50 - 20}{50 + 20}\times 100\% = 43\%
\]

because the pulse time can vary between 20 % and 50 %. When using the pulse current as control parameter, ΔQ/Q is:

\[
\frac{\Delta Q}{Q} = \frac{I_{p_{\text{max}}} t_p - I_{p_{\text{min}}} t_p}{I_{p_{\text{max}}} t_p + I_{p_{\text{min}}} t_p} \times 100\% = \frac{140 - 20}{140 + 20}\times 100\% = 75\%
\]

because the pulse current can vary between 20 A (base current) and 140 A (point 8). Thus it is clear that choosing the pulse current as control parameter gives a maximum relative variation of the energy input and, hence, a maximum control over the welding process.

The optimal values of the program parameters, estimated on the basis of the foregoing considerations are:

Table 9.2 Optimal program parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pulse frequency</td>
<td>1 Hz</td>
</tr>
<tr>
<td>sample frequency</td>
<td>1000 Hz</td>
</tr>
<tr>
<td>pulse time</td>
<td>200-500 ms</td>
</tr>
<tr>
<td>base time</td>
<td>500-800 ms</td>
</tr>
<tr>
<td>pulse current (control parameter)</td>
<td>20-140 A</td>
</tr>
<tr>
<td>base current</td>
<td>20 A</td>
</tr>
<tr>
<td>pulse trigger current</td>
<td>250 A</td>
</tr>
<tr>
<td>base trigger current</td>
<td>150 A</td>
</tr>
<tr>
<td>pulse trigger time</td>
<td>3 ms</td>
</tr>
<tr>
<td>travel speed</td>
<td>0.5 - 1.8 mm/s</td>
</tr>
</tbody>
</table>
Orbital tube welding with feedback control based on frequency mode analysis

The choice of the trigger parameters is based on the results of the experiments performed with pulsed welding current (chapter 5).

The size of the current steps ($\Delta I_p$), used to adjust the pulse current during feedback control, is dependent on the travel speed and has to be determined empirically: if $\Delta I_p$ is too small for a certain value of the travel speed, then the feedback system is too slow and correct penetration can not be maintained; if $\Delta I_p$ is too large, then the welding current (and the weld pool size) is either too large or too small and the feedback system behaves oscillatory.

9.4 Calibration experiments

As has been stated in the previous section, calibration experiments are necessary to estimate the correction current step $\Delta I_p$, but also to determine an appropriate value for the pulse time (between 20% and 50% of the total cycle time), a start value for $I_p$ and a time for stationary arc burning at the beginning of the welding run, necessary to form a weld pool just after ignition. Calibration experiments are also necessary to determine the tuning factor $C$ (see chapter 8).

A number of calibration experiments was carried out, using tubes of different size and chemical composition. The results of these experiments lead to the following conclusions:

- $\Delta I_p = 2-3$ A gives a rapid but non-oscillatory control if $t_p$ is chosen between 20% and 30% and $v$ between 0.5 and 1.8 mm/s;
- a good start value for $I_p$ is 100 A (which provides a control range of 40 A upward and 80 A downward) when the time for stationary arc burning is chosen between 10 and 20 s;
- a tuning factor $C$ between 0.5 and 0.8 gives correct penetration when upward welding, but underpenetration when downward welding;
- a tuning factor $C$ between 1.5 and 2 gives correct penetration when downward welding, but overpenetration when upward welding.
Orbital tube welding with feedback control based on frequency mode analysis

The last two conclusions show that there is not one single value for C which can be used for correct penetration along the entire weld. To deal with this problem, two possible solutions can be considered.

1. Instead of completing an orbital weld in one single pass, the weld can be completed in two upward passes; for example, the first pass from 150° clockwise to 30° and the second pass from 210° counterclockwise to -30° (see Fig. 9.2). In this case the second pass must have an up-slope and a down-slope; for example, an up-slope from 210° to 150° and a down-slope from 30° to -30°.

2. The orbital track can be divided into segments, each having a specific tuning factor, optimized for correct penetration in that segment.

![Diagram](image)

Fig. 9.2 Welding sequence when orbital welding is performed in two upward passes.

The first solution demands travel speed control: after reaching the position at 30° at the end of the first pass, the torch has to move in the reverse direction to the position at 210° (with the current constant at for example I = I₀ and preferably with a higher travel speed) for the second pass. Furthermore, the current in the second pass should start with an up-slope and end with a down-slope.

Besides the fact that in this case the arc moves over the already welded part of the joint and that extra time is involved with this manoeuvre, this type of control also demands more sophisticated equipment (servo motor or stepper motor), increases the complexity of the welding program and puts a restriction on the start position.
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In the case of the second solution the start position can be anywhere along the orbital track once the tuning factors are selected for each segment of the tube. Thus, the start position becomes a parameter which can be included in the welding program as a variable (the next step in the development of the equipment should include the possibility to determine the start position automatically by making use of an absolute position decoder). Since the second solution requires only a minor modification of the welding program, this solution was chosen for further evaluation during the calibration experiments. The number of segments is set at eight, which is sufficient to perform fine tuning for the differences in position.

The operator now has to select three extra variables before welding:

- the tube diameter \(d\);
- the start position \(P\);
- the travel speed \(v\).

The actual tuning factor for a certain segment is chosen from a circular array of eight empirically determined values \(C_0\)–\(C_7\), depending on the start position (see Fig. 9.3). If the start position is \(1G\), then the first value of the tuning factor is \(C_0\) and the last \(C_7\). If the start position is \(3Gd\), then the first value is \(C_2\) and the last \(C_1\) etc. For reasons explained above, the values of \(C_0\)–\(C_3\) lie generally between 1.5 and 2; the values of \(C_4\)–\(C_7\) lie generally between 0.5 and 0.8.

![Diagram showing segments](image)

Fig. 9.3 Definition of segments when orbital welding is performed with the segmented system.
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The segmented system was successfully tested in a number of preliminary experiments. It appears that with this system correct penetration can be achieved for each position and that the weld bead can be tuned from very fine to very course by adjusting the tuning factors of the various segments.

9.5 Applications of the sensor system for in-process penetration control

The IPPC system, modified with the segmented tuning factors, was tested under severe conditions to proof its validity in practice. These severe conditions were simulated by carrying out orbital tube welding experiments with a fixed setting of the IPPC system for different values of the process parameters and using the degree of penetration as quality criterion (see Fig. 9.4). In view of this, experiments were carried out:

- with different travel speeds (section 9.5.1);
- with tubes of different wall thickness (section 9.5.1);
- with tubes of different steel (section 9.5.2).

![Diagram](image)

Fig. 9.4 Schematic presentation of the welding procedure when using the IPPC feedback system.

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9.5.1 Orbital tube welding with different travel speeds using IPPC

As a first test of the feasibility of the feedback system, experiments were carried out for different values of the travel speed to establish the maximum variation in travel speed before penetration errors start to occur or before the correction current starts to move out of range (<20 A or >140 A).

The welding conditions used are listed in Table 9.3 and were selected on the basis of the results obtained with the calibration experiments. For the experiments tubes of Fe 360 steel having a diameter of 60 mm and a wall thickness of 2 or 3 mm were used.

Table 9.3 Welding conditions for orbital welding with different values of the travel speed

<table>
<thead>
<tr>
<th>workpiece</th>
<th>Fe 360 tube; diameter 60 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrode material</td>
<td>tungsten, 2% thoria</td>
</tr>
<tr>
<td>electrode diameter</td>
<td>1.6 mm</td>
</tr>
<tr>
<td>electrode top angle</td>
<td>30°</td>
</tr>
<tr>
<td>arc length</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>shielding gas</td>
<td>He, 21 l/min</td>
</tr>
<tr>
<td>purging gas</td>
<td>Ar, 3 l/min</td>
</tr>
<tr>
<td>start position</td>
<td>1G</td>
</tr>
<tr>
<td>wall thickness (mm)</td>
<td>3</td>
</tr>
<tr>
<td>travel speed (mm/s)</td>
<td>0.8 - 1.4</td>
</tr>
<tr>
<td>pulse current (A)</td>
<td>40 - 140</td>
</tr>
<tr>
<td>base current (A)</td>
<td>20</td>
</tr>
<tr>
<td>pulse trigger current (A)</td>
<td>250</td>
</tr>
<tr>
<td>base trigger current (A)</td>
<td>150</td>
</tr>
<tr>
<td>total cycle time (ms)</td>
<td>1000</td>
</tr>
<tr>
<td>pulse time (ms)</td>
<td>300</td>
</tr>
<tr>
<td>base time (ms)</td>
<td>700</td>
</tr>
<tr>
<td>trigger time (ms)</td>
<td>3</td>
</tr>
<tr>
<td>correction current step (A)</td>
<td>2</td>
</tr>
</tbody>
</table>
Orbital tube welding with feedback control based on frequency mode analysis

The results of the first series of experiments, carried out with tubes having a wall thickness of 3 mm are plotted in Fig. 9.5. This figure shows the pulse current ($I_p + \Delta I_p$) as a function of the welding position (rotation) for four welding runs, performed with different values of the travel speed (0.8, 1.0, 1.2 and 1.4 mm/s). Inspection of the welds shows that correct penetration is achieved during each run along the entire weld and that the overall quality of the weld is excellent.

It was also found that at a travel speed larger than 1.5 mm/s, the weld starts to show penetration errors (underpenetration), which is an indication that the correction current steps are too small to keep up with the travel speed. At a travel speed smaller than 0.8 mm/s the weld starts to show penetration errors in the form of overpenetration. In both cases the pulse current can easily move out of range (> 140 A or < 20 A, respectively).

![Pulse current as function of rotation angle](image_url)

Fig. 9.5 Pulse current as function of rotation angle, using the IPPC system in the case of welding Fe 360 tubes with 3 mm wall thickness for four different travel speeds (0.8, 1.0, 1.2 and 1.4 mm/s).
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In Fig. 9.5 it can be seen that the pulse current profile is significantly different for the different values of the travel speed used. The general trend is that the pulse current decreases with welding time (position, rotation), the rate of decrease becoming smaller with increasing travel speed. It can also be seen that peaks appear in the current profile, the peak between 90° and 180° being the most prominent.
In the beginning of the welding run the matching pulse current for a specific travel speed is adapted by the system; this matching value is lower for lower travel speed.
The overall decrease of the pulse current, observed after adaptation of the matching value, is directly related to the continuous accumulation of heat in the tube. This decrease becomes especially manifest at the end of the welding run when the weld pool meets the approaching heat front.
The pulse current peak, occurring between 90° and 180° and superimposed on the generally decreasing trend of the pulse current, can be qualitatively explained by the fact that in this range the arc length becomes increasingly smaller due to the forward flow of the weld pool between torch and workpiece (see Fig. 6.3). As the arc length is linearly related to the arc voltage, this implies that without correction the heat input would decrease in this range. To compensate for the decrease in heat input, the pulse current must therefore increase. Also the melting efficiency under these conditions is smaller because the arc tends to overheat the liquid metal, instead of melting new solid material.

Similar experiments were carried out with Fe 360 tubes, having a wall thickness of 2 mm. The welding conditions used in these experiments are also listed in Table 9.3. The results obtained are plotted in Fig. 9.6 and are similar to those obtained in the experiments carried out with the tubes having a wall thickness of 3 mm. However, there is only a slight indication of a peak in the downward range of the welding run. This can be readily understood because the phenomenon, responsible for this peak (the forward flow of the weld pool), has a smaller effect due to the smaller average weld pool size.
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Fig. 9.6  Pulse current as function of rotation angle, using the IPPC system in the case of welding Fe 360 tubes with 2 mm wall thickness for four different travel speeds (1.0, 1.2, 1.4 and 1.8 mm/s).

9.5.2 Orbital tube welding with different materials using IPPC

To examine the influence of the tube material on the feasibility of the feedback system, welding experiments were carried out with tubes of unalloyed steel Fe 360 and stainless steel AISI 304, using the same setting of the IPPC system. The welding conditions used are listed in Table 9.4.

It was found that in both cases welds of excellent quality are formed with correct penetration along the entire range.

In Fig. 9.7 the pulse current recorded during welding is plotted as a function of the welding position (rotation) for both Fe 360 and AISI 304. The figure shows that for both
Orbital tube welding with feedback control based on frequency mode analysis

materials the current exhibits an overall decrease with time. Since AISI 304 has a smaller heat conductivity than Fe 360, the pulse current for the AISI 304 weld decreases more rapidly, remaining at a lower average level, than the pulse current for the Fe 360 weld. Another interesting observation is that the pulse current peak, which occurs between 90° and 180° for Fe 360 and was explained above, does not occur for AISI 304. The main reason for this is directly connected with the difference in weld pool shape: due to the smaller heat conductivity, the weld pool in AISI 304 is smaller than in Fe 360, as a consequence of which the effect of the downward flow of the liquid metal is less pronounced.

Table 9.4 Welding conditions for orbital welding with different materials

<table>
<thead>
<tr>
<th>workpiece</th>
<th>Fe 360 and AISI 304 tube; diameter 60 mm, wall thickness 3 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrode material</td>
<td>tungsten, 2% thoria</td>
</tr>
<tr>
<td>electrode diameter</td>
<td>1.6 mm</td>
</tr>
<tr>
<td>electrode top angle</td>
<td>30°</td>
</tr>
<tr>
<td>arc length</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>shielding gas</td>
<td>He, 21 l/min</td>
</tr>
<tr>
<td>purging gas</td>
<td>Ar, 3 l/min</td>
</tr>
<tr>
<td>travel speed</td>
<td>1 mm/s</td>
</tr>
<tr>
<td>start position</td>
<td>1G</td>
</tr>
<tr>
<td>pulse current (A)</td>
<td>40 - 140</td>
</tr>
<tr>
<td>base current (A)</td>
<td>20</td>
</tr>
<tr>
<td>pulse trigger current (A)</td>
<td>250</td>
</tr>
<tr>
<td>base trigger current (A)</td>
<td>150</td>
</tr>
<tr>
<td>total cycle time (ms)</td>
<td>1000</td>
</tr>
<tr>
<td>pulse time (ms)</td>
<td>300</td>
</tr>
<tr>
<td>base time (ms)</td>
<td>700</td>
</tr>
<tr>
<td>trigger time (ms)</td>
<td>3</td>
</tr>
<tr>
<td>correction current step (A)</td>
<td>2</td>
</tr>
</tbody>
</table>
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Fig. 9.7 Pulse current as function of rotation angle, using the IPPC system in the case of welding Fe 360 and AISI 304 tubes with 3 mm wall thickness.

9.6 The influence of the correction current step

To evaluate the significance of the correction current step size ($\Delta I_p$) when using the IPPC feedback system, a series of experiments was carried out with the same setting of the system and the same welding conditions (Table 9.5), but with four different values of the correction current step: 1 A, 2 A, 3 A and 4 A.

The results of these experiments for $\Delta I_p = 1$ A and $\Delta I_p = 4$ A are presented in Fig. 9.8. The figure shows clearly that the overall decreasing trend of the pulse current profile does not depend on the value of $\Delta I_p$. The figure also shows that the fastest correction is achieved when $\Delta I_p = 4$ A. However, the pulse current behaves rather oscillatory and the
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change in heat input is very irregular in this case, which is not beneficial for the weld bead appearance. On the other hand it was found that when \( \Delta I_p = 1 \) A, the correction is too slow to keep up with the heat input required to maintain correct penetration. The optimal correction current step in this situation appears to lie in the range of 2-3 A.

**Table 9.5 Welding conditions for orbital welding with different correction current steps**

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>workpiece</td>
<td>Fe 360; diameter 60 mm, wall thickness 3 mm</td>
</tr>
<tr>
<td>electrode material</td>
<td>tungsten, 2% thoria</td>
</tr>
<tr>
<td>electrode diameter</td>
<td>1.6 mm</td>
</tr>
<tr>
<td>electrode top angle</td>
<td>30°</td>
</tr>
<tr>
<td>arc length</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>shielding gas</td>
<td>He, 21 l/min</td>
</tr>
<tr>
<td>purging gas</td>
<td>Ar, 3 l/min</td>
</tr>
<tr>
<td>travel speed</td>
<td>1 mm/s</td>
</tr>
<tr>
<td>start position</td>
<td>1G</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pulse current (A)</td>
<td>28 - 108</td>
</tr>
<tr>
<td>base current (A)</td>
<td>25</td>
</tr>
<tr>
<td>pulse trigger current (A)</td>
<td>250</td>
</tr>
<tr>
<td>base trigger current (A)</td>
<td>150</td>
</tr>
<tr>
<td>total cycle time (ms)</td>
<td>1000</td>
</tr>
<tr>
<td>pulse time (ms)</td>
<td>200</td>
</tr>
<tr>
<td>base time (ms)</td>
<td>800</td>
</tr>
<tr>
<td>trigger time (ms)</td>
<td>3</td>
</tr>
<tr>
<td>correction current step (A)</td>
<td>1, 2, 3, 4</td>
</tr>
</tbody>
</table>
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Fig. 9.8   Pulse current as function of rotation angle, using the IPPC system in the case of feedback with two different correction current step sizes (1 A and 4 A).

9.7 Orbital tube welding with and without feedback control

To further illustrate the feasibility of the IPPC system, a number of experiments was carried out in the form of double tests: one welding run was made with the IPPC system and one or more control runs were made under the same welding conditions but without the IPPC system. After the runs were completed the results were compared. The experiments were carried out with AISI 304 tubes with a diameter of 60 mm and a wall thickness of 3 mm and the welding conditions used are listed in Table 9.6.
Orbital tube welding with feedback control based on frequency mode analysis

Table 9.6 Welding conditions for orbital welding with or without feedback

<table>
<thead>
<tr>
<th></th>
<th>feedback</th>
<th>no feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>workpiece</td>
<td>AISI 304 tube; diameter 60 mm, wall thickness 3 mm</td>
<td></td>
</tr>
<tr>
<td>electrode material</td>
<td>tungsten, 2% thoria</td>
<td></td>
</tr>
<tr>
<td>electrode diameter</td>
<td>1.6 mm</td>
<td></td>
</tr>
<tr>
<td>electrode top angle</td>
<td>30°</td>
<td></td>
</tr>
<tr>
<td>arc length</td>
<td>1.5 mm</td>
<td></td>
</tr>
<tr>
<td>shielding gas</td>
<td>He, 21 l/min</td>
<td></td>
</tr>
<tr>
<td>purging gas</td>
<td>Ar, 3 l/min</td>
<td></td>
</tr>
<tr>
<td>travel speed</td>
<td>1 mm/s</td>
<td></td>
</tr>
<tr>
<td>start position</td>
<td>3Gd</td>
<td></td>
</tr>
<tr>
<td>pulse current (A)</td>
<td>40-120</td>
<td>40-120</td>
</tr>
<tr>
<td>base current (A)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>pulse trigger current (A)</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>base trigger current (A)</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>total cycle time (ms)</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>pulse time (ms)</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>base time (ms)</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>trigger time (ms)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>correction current step (A)</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Some of the results obtained are presented in Figs. 9.9 and 9.10. Figure 9.9 shows the bead width at the inside of the tube for the situation with feedback control and the bead width for two situations without feedback control (one with a relatively low pulse current and one with a relatively high pulse current). The figure shows that:

- the bead width for the situation with feedback control remains almost constant for the entire weld;
- the bead width increases to an unacceptably large size for the situation without feedback control and a high pulse current (overpenetration);
- the bead width is zero at some locations for the situation without feedback control and low pulse current (underpenetration).

The photographs presented in Fig. 9.10 confirm these observations. Thus, it may be concluded that the IPPC system offers a reliable and effective tool for penetration control during orbital tube welding.
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Fig. 9.9  Bead width at the inside of the welded tube as a function of rotation angle in the case of welding AISI 304 tubes having a diameter of 60 mm and a wall thickness of 3 mm, with and without feedback control.
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\[ \text{Diagram a} \]

\[ \text{Diagram b} \]
Orbital tube welding with feedback control based on frequency mode analysis

Fig. 9.10  Inside view and outside view of orbital weld beads, obtained by welding AISI 304 tubes having a diameter of 50 mm and a wall thickness of 3 mm: a) with feedback control, b) without feedback control and high pulse current and c) without feedback control and low pulse current.

9.8 Conclusions

In this chapter the results of experiments with orbital tube welding using feedback control have been presented and discussed.

It appears that with the modified IPPC program, feedback control is reliable and effective: high quality welds are produced with overall correct penetration during the entire welding operation. The performance of the system does not depend on the start position and the penetration can be tuned from fine to course.

It is also possible to use the feedback system off-line. In that situation a plot of the sum frequency versus time gives a good indication of the quality of the weld.
Orbital tube welding with feedback control based on frequency mode analysis

References


weld pool oscillation for penetration sensing and control

summary

One of the challenges in today’s welding research is sensing and control of weld penetration. This has resulted in the development of a number of different concept versions of penetration sensors, based on various physical phenomena. An important drawback of most of these systems is that they are rather complex and in many cases require access to the backface of the workpiece, which is often not possible. Many of the systems have also a negative effect on weld bead appearance.

This thesis deals with a new approach to penetration sensing, which is based on weld pool oscillation. This approach is simple and straightforward and opens possibilities for sensing over a wide range of applications. In the weld pool oscillation approach, the weld pool is triggered into oscillation by means of short current pulses, superimposed on the welding current and the oscillation frequency is extracted from the arc voltage variation, using Fast Fourier Transform analysis. By monitoring the oscillation frequency during welding, direct information is obtained about the penetration of the weld pool. In the case of partial penetration the pool oscillates in a high frequency mode (mode 1) and in the case of full penetration the pool oscillates in a low frequency mode (mode 3). The difference between the oscillation frequency of mode 1 and mode 3 can easily be detected when monitoring the frequency spectrum and can be used as basis of weld penetration sensing.

A specific drawback of the weld pool oscillation sensing technique is that with this technique only the transition between partial penetration and full penetration (and vice versa) can be detected and that it does not provide quantitative information about the
degree of full penetration. However, in many situations it is demanded to keep the full penetration restricted and preferably as small as possible. A possible way to obtain quantitative information about the degree of full penetration is to make use of pulsed welding current.

During pulsed current GTA welding three different situations can occur, depending on the welding conditions: underpenetration, correct penetration or overpenetration. In the case of underpenetration mode 1 oscillation occurs during both the pulse time and the base time. This situation is characterized by one (high frequency) peak in the frequency distribution. In the case of correct penetration mode 3 oscillation occurs during the pulse time and mode 1 oscillation during the base time. This situation is characterized by two peaks in the frequency distribution (one high frequency peak and one low frequency peak). In the case of overpenetration mode 3 oscillation occurs during both the pulse time and the base time. This situation is characterized by one (low frequency) peak in the frequency distribution. Sensing of weld pool geometry during pulsed current GTA welding is possible by monitoring the peaks in the frequency distribution. Optimal penetration is obtained by maintaining two peaks in the frequency distribution.

In practice it is often necessary that welding is carried out in non-flat positions. This is, for instance, the case in orbital tube welding where the welding position changes continuously during the welding operation. To examine the effect of the welding position on the oscillation behavior of the weld pool, a series of systematic experiments was performed. On the basis of the results obtained it can be concluded that there is no significant difference in oscillation behavior for both the mode 1 and mode 3 oscillations between the flat position and each of the non-flat positions and that it is possible to detect the transitions between underpenetration and correct penetration and between correct penetration and overpenetration by means of frequency mode analysis for every welding position.
The influence of cold wire supply during welding on the oscillation behavior of the weld pool was also investigated. It was found that cold wire supply during welding does not lead to structural changes of the weld pool oscillation, which implies that penetration control by means of oscillation frequency analysis is also possible in the case of cold wire supply. However, it must be realized that the frequency analysis leads to results which are less accurate than those obtained in the case of pulsed GTA welding without wire supply, due to the effect of droplet transfer on the size and temperature of the weld pool.

As a logical next step a feedback system for weld penetration control based on oscillation mode analysis was designed. The system consists of a unit to generate a pulsed welding current with the possibility to generate extra triggering pulses, a unit to sample arc voltage and arc current, a unit for frequency analysis and a unit for current adjustment, based on oscillation mode analysis, to maintain correct penetration. In this program most of the parameters can be defined by the operator. Also special modifications for orbital tube welding were applied.

Attention was also given to spot welding, an alternative approach to in-process control of penetration. However, this approach was not further pursued in view of a number of apparent limitations.

To test the feasibility of the feedback system for in-process penetration control in the case of orbital tube welding, a series of experiments was carried out with tubes of different size and material. It appears that with the feedback program penetration control is reliable and effective: high quality welds are produced with overall correct penetration during the entire welding operation. The performance of the system does not depend on the start position and the penetration can be tuned from fine to course.

It is also possible to use the feedback system off-line for post-welding quality control. In that situation a plot of the sum frequency versus time gives a good indication of the quality of the weld.

Ir. A.J.R. Aendenrooemer
een doorlassingssensor gebaseerd op lasbadoscillatie

samenvatting

Een van de uitdagingen in het huidig onderzoek op het gebied van lastechologie betreft de detectie en controle van de doorlassing (de diepte van de lasverbinding in het werkstuk, die bij voorkeur tot aan de onderkant van het werkstuk moet reiken). Onderzoek op dit gebied heeft geleid tot een verscheidenheid aan doorlassingssensoren, gebaseerd op verschillende fysische verschijnselen. Een groot nadeel van deze sensoren is hun complexiteit en kwetsbaarheid en het feit dat hun toepassing in de meeste gevallen toegang vereist tot de onderkant van het werkstuk, hetgeen in de laspraktijk zelden mogelijk is. Veel van de sensorsystemen hebben bovendien een negatieve invloed op het uiterlijk van de lasverbinding.

In dit proefschrift wordt een nieuwe methode van doorlassingsdetectie, gebaseerd op lasbadoscillaties, beschreven. De methode is eenvoudig van opzet en ongecompliceerd in gebruik en opent mogelijkheden voor doorlassingsdetectie in een groot toepassingsgebied. Volgens deze methode wordt het lasbad in trilling gebracht door middel van korte stroompulsen, gesuperponeerd op de lasstroom. Uit de variaties in de lasspanning, die een gevolg zijn van de trilling, wordt door middel van Fast-Fourier-Transformatie de oscillatiefrequentie berekend.

Door de oscillatiefrequentie tijdens het lassen continu te meten wordt directe informatie verkregen over de mate van doorlassing. In het geval van onvolledige doorlassing trilt het lasbad in een hoogfrequente oscillatiemode (mode 1) en in het geval van volledige doorlassing in een laagfrequente mode (mode 3). Het verschil in oscillatiefrequentie tussen mode 1 en mode 3 kan eenvoudig worden gedetecteerd en kan als basis dienen voor doorlassingsdetectie.
Een nadeel van de methode is dat slechts de overgang tussen onvolledige doorlassing en volledige doorlassing (en vice versa) kan worden gedetecteerd en dat geen kwantitatieve informatie wordt verkregen over de mate van volledige doorlassing (de zwaarte van de las). In veel situaties is het echter vereist dat de doorlassing een beperkte grootte heeft (bij voorkeur zo licht mogelijk).

Om kwantitatieve informatie over de mate van volledige doorlassing te verkrijgen kan gebruik gemaakt worden van pulserende lasstralen. Bij pulserend TIG-lassen zijn er drie mogelijkheden, afhankelijk van de lassituatie: correcte doorlassing, onderrugvormige doorlassing en overmatige doorlassing. In het geval van correcte doorlassing treedt mode 1 oscillatie op tijdens de basistijd en mode 3 oscillatie tijdens de pulstijd. Deze situatie wordt gekenmerkt door twee pieken in de frequentieverdeling (een hoogfrequente piek en een laagfrequente piek). In het geval van onderrugvormige doorlassing treedt mode 1 oscillatie op, zowel tijdens de pulstijd als tijdens de basistijd. Deze situatie wordt gekarakteriseerd door één (hoogfrequente) piek in de frequentieverdeling. In het geval van overmatige doorlassing treedt mode 3 oscillatie op, zowel tijdens de pulstijd als tijdens de basistijd, een situatie die gekarakteriseerd wordt door één (laagfrequente) piek in de frequentieverdeling. Optimale doorlassing gaat dus gepaard met twee pieken in de frequentieverdeling.

In de laspraktijk is het vaak noodzakelijk om in positie te lassen. Dit is bijvoorbeeld het geval bij het orbitaal lassen van pijpen, waar de positie van de lastoorts continu varieert. Het effect van de laspositie op het oscillatiegedrag is systematisch onderzocht. Op basis van de verkregen experimentele resultaten kan geconcludeerd worden dat er geen significant verschil bestaat in oscillatiegedrag tussen de diverse lasposities en dat het voor elke laspositie mogelijk is om de overgang te detecteren tussen onderrugvormige doorlassing en correcte doorlassing, en tussen correcte doorlassing en overmatige doorlassing door middel van frequentie-mode analyse.

Ook is onderzoek gedaan naar de invloed van koude-draad toevoer tijdens TIG-lassen op het oscillatiegedrag van het lasbad. Dit onderzoek heeft uitgewezen dat koude-draad toevoer geen wezenlijke veranderingen in lasbadoscillatie teweegbrengt, hetgeen erop duidt dat doorlassingsdetectie door middel van frequentie-analyse eveneens mogelijk is tijdens het lassen met koude-draad toevoer. Wel moet worden opgemerkt dat de frequentie-analyse tot minder nauwkeurige resultaten leidt dan in het geval van pulserend
TIG-lassen zonder koude-draad toevoer, vanwege het effect van de invallende druppels op de grootte en de temperatuur van het lasbad.

Als logische volgende stap in het onderzoek is een terugkoppelingsysteem ontworpen voor doorlassingscontrole, gebaseerd op frequentie-mode analyse. Dit systeem bestaat uit een module om een pulserende lasstroom te genereren met de mogelijkheid van extra triggerpulsen, een module om de boogspanning en de boogstroom continu te meten, een module voor frequentie-analyse en een module om, gebaseerd op de frequentie-analyse, de stroom aan te passen voor correcte doorlassing. Tevens zijn speciale voorzieningen voor het orbitaal pijplassen in het systeem opgenomen.

Voorts is aandacht besteed aan "spot welding", een alternatieve benadering voor doorlassingscontrole. Vanwege een aantal tekortkomingen van dit proces, is deze benadering echter niet verder doorgezet.

Om de haalbaarheid van het terugkoppelingsysteem voor doorlassingscontrole te testen voor orbitaal pijplassen, zijn experimenten uitgevoerd met pijpen van verschillende afmetingen en samenstelling. Het blijkt dat doorlassingscontrole met behulp van het terugkoppelingsysteem betrouwbaar en succesvol is: de geproduceerde lassen zijn van hoge kwaliteit met een consistente correcte doorlassing over de gehele lasomtrek. De startpositie is niet van invloed op het functioneren van het systeem en de doorlassing kan worden afgestemd van zeer licht tot zeer zwaar.

Het is ook mogelijk om het terugkoppelingsysteem "off-line" te gebruiken voor kwaliteitscontrole achteraf. In deze toepassing kan een uitdraai worden gemaakt van het verloop van de oscillatiefrequentie tijdens het lassen, hetgeen een goede indicatie geeft over de kwaliteit van de las.

Ir. A.J.R. Aendenroomer
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curriculum vitae

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