Stellingen

behorende bij het proefschrift

Additives in GTA welding

Wilma Middel

22 september 2000

1. Het orbitaal TIG-lassen met SiO₂ levert een gratis eindstop op.

2. In tegenstelling tot wat veel onderzoekers veronderstellen speelt Marangoni-stroming een ondergeschikte rol bij het lassen met additieven.

3. Te vaak wordt de analyse van experimentele resultaten tot model gebombardeerd.

4. De potentie van de doorlassingssensor gebaseerd op lasbadoscillaties wordt door de industrie onderschat.

5. Door bij plasmasnijden additieven toe te passen worden de eigenschappen van de snijkanten uniformer.

6. Ten behoeve van inzichtelijk onderwijs moeten oude, niet-geautomatiseerde opstellingen gehandhaafd worden naast de gemoderniseerde opstellingen.

7. Om meer automobilisten van het type ‘heer in het verkeer’ te creëren zou de groep rijders van het type ‘opzij-opzij-opzij’ verplicht een maand moeten forensen in een boodschapenautootje.

8. De geschiedenis had er anders uitgezien als Damocles een paard en Troje een zwaard had gehad.
9. De overheid heeft zichzelf de ultieme rechtvaardiging voor het rekeningrijden bezorgd door Vinex locaties aan te leggen zonder te zorgen voor goed openbaar vervoer.


11. De waarschuwing ‘haal niet in en blijf rechts rijden’ suggereert dat spookrijders nooit inhalen en altijd rechts rijden.

12. De vooronderstelling dat bij verzekeringen de grote massa betaalt voor de uitzonderingsgevallen is onjuist gezien de hogere verzekeringspremies voor de laatsten.

13. De papieren rompslomp die het melden van bijna-ongelukken met zich meebrengt, heeft een averechts effect op de veiligheid.

14. Een flat heeft geen verdiepingen.

15. MS-help suggereert dat je met één druk op F1 van een ernstige ziekte kunt genezen.
Additives in GTA welding
Additives in GTA welding

proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. ir K.F. Wakker,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op vrijdag 22 september 2000 om 16.00 uur

doors

Wilhelmina MIDDEL

doctorandus in de scheikunde
geboren te Tiel
Dit proefschrift is goedgekeurd door de promotor:
Prof. dr G. den Ouden

Samenstelling promotiecommissie:

Rector Magnificus, voorzitter
Prof. dr G. den Ouden, Technische Universiteit Delft, promotor
Prof. dr R. Boom, Technische Universiteit Delft
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Prof. dr J.H.W. de Wit, Technische Universiteit Delft

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Wilma Middel
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<th>Name</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>surface area</td>
<td>m²</td>
</tr>
<tr>
<td>B</td>
<td>magnetic induction</td>
<td>T</td>
</tr>
<tr>
<td>b₀</td>
<td>impact parameter</td>
<td>m</td>
</tr>
<tr>
<td>c</td>
<td>specific heat</td>
<td>kJkg⁻¹K⁻¹</td>
</tr>
<tr>
<td>D</td>
<td>weld pool depth</td>
<td>mm</td>
</tr>
<tr>
<td>d</td>
<td>weld pool diameter</td>
<td>mm</td>
</tr>
<tr>
<td>E</td>
<td>electric field strength</td>
<td>Vm⁻¹</td>
</tr>
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<td>e</td>
<td>elementary charge</td>
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<tr>
<td>E_d</td>
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<td>eV</td>
</tr>
<tr>
<td>E_i</td>
<td>ionization energy</td>
<td>eV</td>
</tr>
<tr>
<td>f</td>
<td>frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>F_b</td>
<td>buoyancy force</td>
<td>N</td>
</tr>
<tr>
<td>F_L</td>
<td>Lorentz force</td>
<td>N</td>
</tr>
<tr>
<td>g</td>
<td>gravitational constant</td>
<td>9.8 ms⁻²</td>
</tr>
<tr>
<td>g_i</td>
<td>statistical weight corresponding to the energy level u_i</td>
<td>m</td>
</tr>
<tr>
<td>h</td>
<td>Debye shielding distance</td>
<td>m</td>
</tr>
<tr>
<td>I</td>
<td>electric current</td>
<td>A</td>
</tr>
<tr>
<td>j</td>
<td>current density</td>
<td>A m⁻²</td>
</tr>
<tr>
<td>k</td>
<td>Boltzmann constant</td>
<td>1.38·10⁻²³ JK⁻¹</td>
</tr>
<tr>
<td>l_e</td>
<td>electron mean free path</td>
<td>m</td>
</tr>
<tr>
<td>m_e</td>
<td>mass of electron</td>
<td>9.109·10⁻³¹ kg</td>
</tr>
<tr>
<td>n_e</td>
<td>electron density</td>
<td>m⁻³</td>
</tr>
<tr>
<td>p</td>
<td>pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>ΔQ</td>
<td>heat flowing through unit surface area per unit time</td>
<td>Wm⁻²</td>
</tr>
<tr>
<td>Q</td>
<td>collision cross-section</td>
<td>m²</td>
</tr>
</tbody>
</table>
$S_i$  total angular momentum quantum number of the $i^{th}$ electronic energy level
$T$  absolute temperature  \( \text{K} \)
$V$  voltage  \( \text{V} \)
$v$  travel speed  \( \text{mms}^{-1} \)
$W$  weld pool width  \( \text{mm} \)
$\alpha_d$  degree of dissociation
$\alpha_i$  degree of ionization
$\beta$  thermal expansion coefficient  \( \text{K}^{-1} \)
$\varepsilon_f$  strain to fracture
$\gamma$  surface tension  \( \text{Nm}^{-1} \)
$\eta_m$  melting efficiency
$\kappa$  heat conduction coefficient  \( \text{Wm}^{-1}\text{K}^{-1} \)
$\rho$  specific mass  \( \text{kgm}^{-3} \)
$\sigma$  electrical conductivity  \( \Omega^{-1}\text{m}^{-1} \)
$\sigma_u$  ultimate tensile strength  \( \text{Nm}^{-2} \)
$\sigma_y$  lower yield point  \( \text{Nm}^{-2} \)
INTRODUCTION

As long as the human race uses metals for handcraft, there has been a quest for ways to join metal parts. In Egypt already in the Bronze Age (ca. 3000 BC-1100 BC) a joining process was known, which is nowadays referred to as hard soldering. The godfather of modern arc welding is Sir Humphry Davy, who discovered the carbon arc in 1801 [1.1, 1.2]. Although it took about 80 more years before the carbon arc was found to be of practical use in joining, this invention caused an avalanche of new joining processes (Fig. 1.1). The first patent on carbon arc welding originates from 1885 and was filed by Nikolai N. Benardos [1.3]. As in many industrial applications, the second world war caused the start of a rush for new joining processes. In the years 1940-1965, the most common welding processes, like Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW), Plasma Arc Welding (PAW), Laser Welding and Electron Beam Welding were developed [1.4]. Nowadays, arc welding is one of the most important joining processes in industrial applications. During the last thirty years of the 20th century, only few new processes for joining have been invented, the most important being Powder Plasma Arc Welding (PPAW), friction stir welding, ATIG Welding and hybrid welding processes like laser-GTA welding.
In spite of the fact that few new processes are being invented, still a great deal of research is being carried out with the aim to understand and model the phenomena that accompany the arc welding process. This makes it possible to further improve the existing processes.

More recently, research focuses on automation and control of welding processes, as industry asks for quality improvement and increase of productivity. This requires the development of sensors and control systems, which make it possible to automate the entire welding process and to control the weld quality in real time.

This thesis seamlessly connects to the demand for research in the area of innovation and automation. Its ultimate aim is to obtain fundamental insight in the effect of the use of certain chemical compounds, in the following referred to as additives, on the Gas Tungsten Arc Welding process and to explore the possibilities of using additives as a tool for process improvement and process automation.
Introduction

It appears that the application of additives during GTA welding strongly influences weld pool formation. Most additives cause an enhancement in weld penetration, which is interesting in terms of process efficiency. This observation induced a thorough study of the mechanisms playing a role when using additives during welding, which resulted in a better comprehension of weld pool processes.

Obviously, additives not only influence the weld pool, but also the welding arc. This initiated the idea to study and test the feasibility of a new seam tracking sensor to be applied during GTA welding. This new approach finds its basis in the influence that additives have on the physical and electrical properties of the welding arc, in particular on arc voltage. It is proposed that this change in arc voltage can be used for real time position sensing by marking the weld seam with additives. A deviation of the weld seam will cause a deviation in arc voltage, which can be monitored and subsequently used for feedback control in real time.

In Chapter 2, the basics of the Gas Tungsten Arc Welding process are described and a short review of the physical and chemical processes that occur in the welding arc is given. Furthermore, the mechanisms playing a role in weld pool formation is dealt with.

The influence of different additives on the welding arc under standard welding conditions is discussed in Chapter 3. Additional experiments with SiO₂ under varying welding conditions serve to obtain more insight in the different mechanisms that play a role. For the same purpose, photographs are taken of the arc during welding and some spectroscopic measurements are carried out.

Chapter 4 deals with the influence of additives on the weld pool. A large series of experiments is carried out to map the influence of additives on the weld pool as a function of different welding parameters. Based on these experiments, it is determined which mechanisms in weld pool formation are affected by the use of additives. In addition, attention is paid to the microstructure and the mechanical properties of the welds obtained. A literature review of different sensors used during welding is given in Chapter 5.

In Chapter 6 attention is given to the applicability of additives to improve the GTA welding process in terms of enhanced penetration. In addition, the feasibility of the new position sensing system is tested and discussed.
Chapter 1

References


1.3 N.N. de Benardos, US00379453 (March 1888), US 00380554 (April 1888), US00388245 (August 1888)

THEORETICAL BACKGROUND

Electric arc welding is a widely used process for joining metals in industry. Sir Humphry Davy, who discovered the electric arc in 1801, founded the process [2.1]. Although welding with ordinary fire already was applied before the Renaissance [2.2], it took quite a long time before the electric arc became of practical use in welding.

The first gas shielded arc welding process operated with argon or helium as shielding gas and a tungsten electrode. This process became known as the gas tungsten arc (GTA) or tungsten inert gas (TIG) welding process. In GTA welding, a tungsten electrode is used as non-melting electrode. Usually, 1-2% thoria or zirconia is added to the tungsten electrode for stabilization purposes and to facilitate electron emission. An inert shielding gas is used to protect the electrode and the liquid metal in the weld pool from the surrounding atmosphere. GTA welding is especially suited to weld thin plates, small parts and root passes in larger workpieces.

To obtain more insight in the phenomena playing a role in arc welding, a brief description of these processes will be given in the next sections, with emphasis on the GTA welding process.
2.1 Gas tungsten arc welding

The welding arc is an electric discharge in a partially ionized gas (plasma). It is usually operated at an arc length of a few millimeters and under these conditions it is characterized by a relatively low voltage (10 to 40 V) and a relatively high current (10 to 1000 A). These characteristics make the electric arc distinguishable from other types of gas discharges, like the glow discharge, the corona discharge and lightning. A typical example of an arc voltage-arc current characteristic is depicted in Fig. 2.1. It appears that arc voltage usually decreases with arc current up to about 50 A and slightly increases at higher currents. The arc voltage-arc current characteristic depends on arc length, shielding gas composition and the chemical composition of anode and cathode.

The current flowing through the arc can have almost any value above a certain minimum. This lower limit exists because the plasma temperature decreases with decreasing arc current, resulting in insufficient plasma ionization. In general no upper limit exists for the arc current, although the arc can be destabilized by plasma turbulence at high values of the arc current.

![Graph](image)

**Fig. 2.1** Typical arc voltage-arc current characteristic of a gas tungsten arc.
Theoretical Background

Usually, the welding arc is divided in three different regions (Fig. 2.2): the anode fall region, the cathode fall region and the arc column. It appears that the arc voltage behaves non-linear: in the fall areas, the arc voltage changes abruptly, due to the space charge present as will be discussed below.

![Diagram of the welding arc and its potential distribution.](image)

**Fig. 2.2** Schematic representation of the welding arc and its potential distribution.

**Arc column**

The arc column, which covers the largest part of the welding arc, exists of neutral particles, like atoms and molecules, and charged particles, like electrons and ions. One of the most important features of the arc column is its electric neutrality. The number of electrons in a volume-unit equals the number of positive ions, resulting in a space charge that equals zero. This means that the gas present in the arc column can be considered to be a plasma and that the well-established plasma physics theories can be applied.

According to Poisson’s law, the change in electric field strength with distance can be described by:

\[
\frac{d^2V}{dx^2} = \frac{dE}{dx} = -4\pi \rho
\]

(2-1)

in which \(V\) is the voltage, \(x\) the distance, \(E\) the electric field strength and \(\rho\) the space charge per volume unit.
Chapter 2

The fact that the arc column is electrically neutral implies that the electric field strength in the arc column should be constant.

The magnitude of the electric field strength, which is normally about $10^3 \text{ V/m}$, can be determined by measuring the arc voltage as a function of arc length. The slope of the straight line obtained represents the actual electric field strength.

Another important aspect of the plasma in the arc column is the fact that it can be considered to be in Local Thermodynamic Equilibrium (LTE). This means that between the different particles present in the arc column a complete energy exchange takes place by mutual collisions as a consequence of which all particles have the same average kinetic energy. In other words: electrons and heavy particles have the same temperature.

The plasma temperature in the arc column depends on the composition of the shielding gas and on the arc current. It can be as high as 5000 °C in the case of metal vapors present and as high as 25000 °C in the case of a pure inert gas arc.

**Cathode fall region**

The cathode fall region is a very narrow boundary layer (~$10^{-8} \text{ m}$) between cathode and arc column. This region is characterized by a positive space charge and the voltage fall over this layer has a value in the range of 10-20 V, depending on the shielding gas and the chemical composition of the cathode material. Hence, the mean electric field strength is about $10^9 \text{ V/m}$. Due to the high electric field and the small number of particles in this layer, the energy exchange by collisions will not be complete. As a consequence no thermodynamic equilibrium exists and the electron temperature will be much lower than the heavy particle temperature.

The most important task of the cathode is to emit electrons, which will be transported in the direction of the anode under influence of the electric field. One of the important mechanisms to liberate electrons from the cathode is thermionic emission, which can be expressed in terms of the Richardson equation:

$$j_e = AT^2 \exp\left(-\frac{e\phi}{kT}\right)$$

(2-2)
in which \( j_e \) represents the electron current density, \( A \) a constant (for metals about \( 6 \times 10^3 \text{Am}^{-2}\text{K}^{-2} \)), \( e \) the elementary charge, \( \varphi \) the work function, \( k \) the Boltzmann constant and \( T \) the absolute temperature.

To prevent the tungsten electrode to melt, thoria or zirconia is usually added in small amounts. Due to the lower work function of these oxides (~2 eV) in comparison with the work function of metals (~4-5 eV), the temperature of the cathode can be kept at a lower level.

When the temperature of the cathode is low, the required number of electrons can not be produced by thermionic emission alone and field emission of electrons starts playing a role. Besides a high electric field strength, a high current density is required for field emission, resulting in contraction of the arc and formation of the so-called cathode spot. Both in the case of thermionic emission and in the case of field emission, the presence of oxides is essential: the cathode spot prefers places on the surface of the cathode where oxide is located.

**Anode fall region**

The anode fall region is the thin boundary layer (~10^{-7} m) between anode and arc column, characterized by a negative space charge and a voltage fall of about 1-10 V, depending on the shielding gas and the chemical composition of the anode material. The mean electric field strength in this region can be as high as 10^7 V/m. Due to the high electric field and the modest collision frequencies between the various particles, the electron temperature is significantly higher that the heavy particle temperature.

At low welding current (I < 40 A), arc contraction occurs in front of the anode. Usually, the so-called anode spot jumps from one place to another, resulting in an unstable behavior of the welding arc.

Because the anode has to receive electrons and because it is unable to produce positive ions, the resulting discontinuity has to be compensated by ionization in the anode fall area. The formed ions are transported in the direction of the arc column, while the produced electrons are moving towards the anode.

The properties of the electric arc as briefly described in the foregoing make it very suitable to be used as heat source for welding. Because of the heat transferred from the arc, the workpiece will be heated and partially melt. Subsequently, the molten metal will cool down, solidify and form the desired joint.
2.2 Physical aspects of the welding arc

2.2.1 Ionization

The most important parameter governing arc plasma behavior is the plasma temperature. To maintain a sufficiently large degree of ionization, the plasma temperature has to exceed about 10000 K for an arc in inert gas and about 5000 K in the case of metal vapor arcs. The degree of ionization $\alpha_i$ depends strongly on temperature and can be expressed by Saha’s equation [2.3]:

$$\frac{\alpha_i^2}{1 - \alpha_i^2} = C_i \frac{T^{5/2}}{p} \exp\left(\frac{E_i}{kT}\right)$$

(2-3)

in which $\alpha_i$ represents the degree of ionization, $C_i$ a constant, $T$ the absolute temperature, $p$ the pressure, $E_i$ the ionization energy and $k$ the Boltzmann constant.

In this equation, the ionization energy $E_i$ plays an important role. In Table 2.1 the ionization energy of some molecules and atoms is given [2.4].

Table 2.1 Ionization energy $E_i$ of some molecules and atoms.

<table>
<thead>
<tr>
<th>Element</th>
<th>$E_i$ (eV)</th>
<th>Element</th>
<th>$E_i$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>13.6</td>
<td>O</td>
<td>13.6</td>
</tr>
<tr>
<td>H₂</td>
<td>15.6</td>
<td>O₂</td>
<td>12.5</td>
</tr>
<tr>
<td>He</td>
<td>24.6</td>
<td>F</td>
<td>17.4</td>
</tr>
<tr>
<td>Ar</td>
<td>15.8</td>
<td>Na</td>
<td>5.1</td>
</tr>
<tr>
<td>C</td>
<td>11.3</td>
<td>K</td>
<td>4.3</td>
</tr>
<tr>
<td>CO</td>
<td>14.1</td>
<td>Ca</td>
<td>6.1</td>
</tr>
<tr>
<td>CO₂</td>
<td>14.4</td>
<td>Fe</td>
<td>7.9</td>
</tr>
<tr>
<td>N</td>
<td>14.5</td>
<td>Si</td>
<td>8.1</td>
</tr>
<tr>
<td>N₂</td>
<td>15.5</td>
<td>Ti</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mg</td>
<td>7.6</td>
</tr>
</tbody>
</table>
As can be concluded from Table 2.1 and can be seen in Fig. 2.3, metals will be more easily ionized in the welding arc than non-metals, because of their lower ionization energy. This implies that the electrical conductivity of the welding arc is strongly affected by the presence of metal vapor.

### 2.2.2 Electrical conductivity

The electrical conductivity is another significant arc parameter. It is directly related to the degree of ionization and plays a decisive role in the heat balance of the arc. The electrical conductivity, $\sigma$, can be expressed as:

$$\sigma = \frac{j}{E} = \frac{e^2 n_e l_e}{\sqrt{8m_e kT / \pi}}$$

(2-4)

with $j$ the current density, $E$ the electric field strength, $e$ the elementary charge, $n_e$ the electron density, $l_e$ the electron mean free path, $m_e$ the electron mass, $k$ the Boltzmann constant and $T$ the absolute temperature.

Both the electron mean free path and the electron density are only dependent on temperature. This means that also the electrical conductivity is a function only of temperature.

![Degree of ionization of some elements as function of the temperature.](image)

Fig. 2.3 Degree of ionization of some elements as function of the temperature.
The electrical current flowing through the arc column is the sum of the electron current and the ion current. A good estimate for the ratio between electron current density and ion current density is given by the equation:

\[
\frac{j_e}{j_i} = \sqrt{\frac{m_i}{m_e}} \tag{2-5}
\]

in which \(j_e\) is the electron current density, \(j_i\) the ion current density, \(m_e\) the electron mass and \(m_i\) the ion mass.

Equation (2-5) shows that in the arc column by far the largest part of the current is carried by electrons.

### 2.2.3 Dissociation

In case of a diatomic gas, part of the molecules will be dissociated under the influence of the temperature. The degree of dissociation is depending on temperature according to the following equation:

\[
\frac{4\alpha_d^2}{1 - \alpha_d^2} = C_2 \frac{T^{5/2}}{p} \exp\left(-\frac{E_d}{kT}\right) \tag{2-6}
\]

in which \(\alpha_d\) represents the degree of dissociation, \(C_2\) a constant, \(T\) the absolute temperature, \(p\) the pressure, \(E_d\) the dissociation energy and \(k\) the Boltzmann constant.

The dissociation energy of some molecular gases is listed in Table 2.2. Using these values, the dissociation degree as a function temperature can be calculated. The results obtained are depicted in Fig. 2.4.

<table>
<thead>
<tr>
<th>gas</th>
<th>(E_d) (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(_2)</td>
<td>4.48</td>
</tr>
<tr>
<td>O(_2)</td>
<td>5.08</td>
</tr>
<tr>
<td>N(_2)</td>
<td>9.76</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>4.30</td>
</tr>
</tbody>
</table>
Fig. 2.4 Degree of dissociation as a function of temperature of some molecular gases.

2.2.4 Heat transport in the welding arc

One of the most important properties of the welding arc is the fact that the potential distribution is non-linear. Due to this non-linear potential behavior, a large part of the total arc power is for the benefit of the fall areas. As can be expected, the energy generated in the arc will not be completely transferred to the workpiece. An important parameter in this respect is the process efficiency, which is defined by the heat transferred to the workpiece per unit time divided by the heat produced by the arc per unit time, or:

\[ \eta_p = \frac{Q}{VI} \]  \hspace{1cm} (2-7)

in which \( Q \) represents the heat transferred to the workpiece per unit time, \( V \) the arc voltage and \( I \) the welding current.
Chapter 2

Arc column
The total amount of heat produced in the arc column per unit of volume can be expressed by the following equation:

\[ Q = \sigma E^2 \]  \hspace{1cm} (2-8)

with \( \sigma \) the electrical conductivity of the arc plasma and \( E \) the electric field strength.
In principle, the transport of the generated heat takes place by three different processes, viz. heat conduction, convection and radiation.
The heat conduction of the electric arc can be characterized by the heat conduction coefficient \( \kappa \), which is defined by the equation:

\[ \Delta Q = \kappa \frac{dT}{dx} \]  \hspace{1cm} (2-9)

with \( \Delta Q \) the heat flowing through a unit surface per unit time and \( dT/dx \) the temperature gradient in the \( x \) direction.

Several mechanisms play a role in the heat conduction of a plasma. First of all, the heat is transported by collisions between heavy particles in the arc (\( \kappa_h \)) and between electrons and heavy particles (\( \kappa_e \)). In addition, part of the energy is transferred by the diffusion and recombination of ionized pairs (\( \kappa_i \)). In the case of molecules, the diffusion and recombination of dissociated pairs can also play a role (\( \kappa_d \)). These different mechanisms result in the total heat conduction coefficient:

\[ \kappa = \kappa_h + \kappa_e + \kappa_i + \kappa_d \]  \hspace{1cm} (2-10)

Heat transport by convection in the welding arc is caused by the temperature differences in the arc, which induce density differences in the column. In addition, electromagnetic forces in the arc give rise to convection, which is mostly referred to as the plasma jet.

Normally, the radiation emitted by the welding arc consists of a line spectrum and a background continuum. When the temperature in the welding arc is high enough, it can be
considered to be a black body. In this case, the total energy emitted by the arc can be described by the Stefan-Boltzman law:

\[ S(T) = cT^4 \] (2-11)

in which \( c \) is a constant.

**Anode fall region**

The heat input to the anode, \( Q_a \), can be expressed by the following equation:

\[ Q_a = V_a I + \frac{3k \Delta T}{2e} I + \frac{\phi_a}{e} I + c_a V_p I \] (2-12)

in which \( V_a, I, k, \Delta T, e, \phi_a, c_a \) and \( V_p \) represent the anode fall voltage, the arc current, the Boltzmann constant, the temperature difference between arc plasma and anode, the elementary charge, the work function of the anode material, a constant and the voltage drop over the arc column, respectively.

The first term on the right hand side of this equation represents the energy produced in the anode fall region, while the second term describes the energy that is liberated when cooling the electrons from plasma temperature to anode temperature. The third term accounts for the energy that is produced by electrons entering the anode, whereas the last term described the energy that is transported from arc column to the anode fall region.

From Eq. (2-12) it can be concluded that \( Q_a \) is proportional to the welding current and only for a small part depends on arc voltage.
Chapter 2

Cathode fall region
In a similar way as in the case of the anode, the heat balance for the cathode can be expressed by the equation:

\[ Q_c = V_c I - \frac{3k\Delta T}{2e} I - \frac{\phi_c}{e} I + c_c V_p I \] (2-13)

Comparison of Eq. (2-12) and Eq. (2-13) leads to the conclusion that, generally speaking, \( Q_a \) is greater than \( Q_c \).

2.3 The weld pool

During arc welding, an electric arc is struck between electrode and workpiece. Part of the heat generated in the arc can be used to locally melt the workpiece, thus forming a weld pool. Under travelling conditions, the base material in front of the arc is melted, while on the backside of the arc the molten metal solidifies. If necessary, additional material can be added by using a consumable electrode. After solidification a joint is established between the two parts to be welded.

The shape of the weld pool is determined by two mechanisms: heat conduction and flow of the liquid metal in the weld pool. In case of a three-dimensional heat flow (thick plate), heat conduction alone would result in a weld pool characterized by a depth/width (D/W) ratio somewhat smaller than 0.5. The fact that in practice the D/W ratio often significantly deviates from this value implies that flow in the weld pool also plays a role.

Generally speaking, two types of fluid flow can occur in the weld pool (Fig. 2.5): radially outward directed flow (type A) and radially inward directed flow (type B). As can be seen in the figure, the shape of the weld pool strongly depends on the direction of the fluid flow. A flow of type A results in a relatively wide and shallow weld pool, whereas a flow of type B causes a narrow and deep weld pool. The occurring flow is caused by a combination of forces: electromagnetic forces, forces caused by variations in the surface tension, forces caused by local variations in the specific temperature of the liquid metal and forces due to the plasma jet.
Fig. 2.5 Two types of fluid motion in the weld pool: a) radially outward directed flow (type A), b) radially inward directed flow (type B).

2.3.1 Electromagnetic forces

Due to the divergence of the electric current, electromagnetic forces (Lorentz forces) can influence the flow of the liquid metal in the weld pool. The Lorentz force $F_L$ is determined by the current density $j$ and the magnetic field $B$ and can be expressed by the equation:

$$ F_L = j \times B $$

(2-14)

Under normal welding conditions, the welding current is divergent. Consequently, the Lorentz force will cause a downward force on the liquid metal in the center of the weld pool, resulting in a flow of type B. It is evident that the Lorentz force is not only operating on the weld pool, but also on the welding arc. In fact, the Lorentz force leads to the generation of the plasma jet, which can play an important role in the heat balance of the welding arc, especially at higher welding currents.
2.3.2 Variation in surface tension

Generally speaking, a temperature gradient exists across the weld pool surface, whereby the temperature in the middle of the pool (under the arc) will be maximum, and minimum at the edges of the weld pool (melting point of the material). Due to the temperature gradient, variations in surface tension will exist across the weld pool surface.

![Surface tension graph](image)

Fig. 2.6 Surface tension of iron as a function of temperature.
A: pure iron, B: iron containing sulfur, C: iron containing oxygen.

For pure metals the surface tension decreases with increasing temperature (the surface tension gradient $\partial \gamma / \partial T$ is negative), as is shown by line A in Fig. 2.6. The resulting flow in the weld pool (Marangoni flow) is therefore of type A. However, the presence of low concentrations of surface active elements, like oxygen, sulfur and selenium, can substantially alter the magnitude and sign of the surface tension gradient (Fig. 2.6, line B
and line C) [2.5-2.7]. Under these conditions a Marangoni flow of type B will be generated in the weld pool, resulting in a narrow and deep weld pool shape. In addition, impurities like calcium and aluminum may affect the flow in the weld pool. This can occur if they react with surface active elements to form compounds which are not surface active, thus hampering the surface active elements in influencing the surface tension gradient [2.8].

2.3.3 Variation in specific mass (buoyancy force)

In general, the liquid metal at the edges of the weld pool has the lowest temperature, and consequently the largest density, whereas the liquid metal in the middle of the weld pool will have the highest temperature and the lowest density. Therefore, the liquid metal at the edges of the weld pool will move downward, while the metal at the center of the weld pool will flow upward. This causes a liquid metal flow of type A. The driving force of the liquid flow is the buoyancy force $F_b$, expressed by [2.9]:

$$\bar{F}_b = \rho \beta g (T - T_0)$$  \hspace{1cm} (2-15)

in which $\rho$ represents the density of the liquid metal, $\beta$ the volumetric thermal expansion coefficient, $g$ the gravitational constant, $T$ the actual temperature and $T_0$ the reference temperature.

In general, the effect of the buoyancy force is small compared to the effect of electromagnetic forces and forces due to differences in surface tension.

2.3.4 Forces due to the plasma jet

At high welding currents, a plasma jet is formed in the arc due to the Lorentz force acting on the arc. The plasma jet causes a drag force along the surface of the weld pool, which results in an outward directed liquid metal flow (type A). Normally, it is assumed that at welding currents below 200 A this drag force is of minor importance. At higher currents, however, the plasma jet starts to dominate the liquid fluid flow more and more [2.9], although Lin and Eagar [2.10] state that the plasma jet has only a significant influence above a welding current of 500 A.
2.4 Concluding remarks

In the foregoing, a brief description of the basic features of the GTA welding process is given, with emphasis on the welding arc and the weld pool. This description refers to welding under ideal conditions and forms the basis and starting point of the present study, which deals with the effects of additives on the GTA welding process. It is evident that additives affect both the welding arc and the weld pool. The effect of additives on the welding arc will be addressed in Chapter 3, whereas Chapter 4 deals with the effect of additives on weld pool formation.
Theoretical Background

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THE INFLUENCE OF ADDITIVES ON THE WELDING ARC

Although many attempts have been made in the past to model the welding arc, it is still a challenge to develop an integral model covering the total system of anode, anode fall region, arc column, cathode fall region and cathode. Of the different parts of the welding arc, the physics of the arc column are probably best understood until now because in the arc column local thermodynamic equilibrium exists, justifying the application of normal plasma physics. As a consequence, different stand-alone models have been developed for the arc column. The fall regions, however, are more difficult to deal with, in particular because of the space charge present. Another complication is that the welding arc can not be considered as consisting of a pure mono-atomic inert gas because of the melting and vaporizing of the material being welded. In fact, it appears that even minor changes in workpiece composition can influence the process quite strongly.

This chapter focuses on the different manifestations of additives and their influence on the behavior and properties of the welding arc, the ultimate aim being to select specific
additives, which can be used for position sensing during GTA welding. Firstly, a short review is given concerning research carried out in this area thus far. This is followed by the presentation of the results of a large number of GTA welding experiments, aimed at mapping the influence of additives on the arc under real welding conditions. Starting point is the selection of suitable additives, i.e. additives that are expected to have a significant influence on the welding arc. With a number of these additives additional experiments are carried out to obtain more insight in the mechanisms playing a role. Experiments with varying arc length, welding current and travel speed are performed. To visualize the effects of additives on the welding arc, photographs are taken during welding. Furthermore, spectroscopic measurements are carried out to obtain information about the different particles present in the arc. In the discussion, efforts are made to explain the obtained results in terms of the different phenomena occurring in the arc.

3.1 Literature review

3.1.1 The effect of minor elements

The research dealing with the effects of minor elements on the welding arc has been reviewed up to 1976 by Glickstein and Yenisavich [3.1]. Since then, different attempts have been made to understand and model the welding arc [3.2-3.4]. Most of the studies focus on the effect of metal vapors on the welding arc. Many researchers [3.1, 3.5-3.8] state that the decisive property of the base material impurities is the ionization potential. Generally speaking, metallic elements have ionization potentials that are much smaller than that of argon [3.9]. It is established that even small amounts drastically affect the arc configuration and the current density distribution. In addition, it has been noted by Block-Bolten and Eagar [3.10] that small changes in concentration of a minor element in the melt may produce large changes in the concentration of the element in the gas phase. This is said to be due to the partial pressure of the vapor above the molten alloy.

To demonstrate the large modification of arc properties caused by minor elements, Glickstein calculated the thermal and electrical conductivity of argon and helium plasmas seeded with small amounts of aluminum [3.8]. Based on this binary model he found that even small concentrations of aluminum significantly influence the electrical conductivity of
the arc. However, Dunn, Allemand and Eagar observed very properly Glickstein’s model to be ‘inadequate in that it considers only the addition of aluminum to a pure inert gas’ [3.11]. In real welding processes the arc will not only contain argon or helium, but also a mixture of iron, manganese, chromium and other metal vapors originating from the base material, which is confirmed by spectroscopic experiments [3.6, 3.12]. Therefore, the influence of an additive on the welding arc will be less dramatic than predicted by a binary model.

3.1.2 The effect of fluxes

In 1965 an improved welding process was introduced by the Paton Welding Institute in the former Soviet Union [3.13, 3.14]. In this process an activating flux, containing several oxides and/or halogenides is applied on the surface of the base material before welding, resulting in an improved weld penetration. While in first instance this method only was applied for welding titanium alloys, later on the method was made applicable for welding steel as well [3.15, 3.16]. Recently, it has been introduced in Western Europe as the A-TIG welding process.

Several mechanisms and explanations have been proposed to account for the improved weld penetration [3.17- 3.25]. Most researchers [3.20-3.25] believe that the improvement is due to arc contraction caused by the formation of negative ions in the outer regions of the arc.

3.2 Selection of additives

As stated above, an important aim of this study is to identify additives, which can be used for position sensing during arc welding. This means that candidate additives should have a significant influence on the physical properties of the welding arc. In addition they should be cheap, not harmful for the environment, easy to obtain and easy to apply. Furthermore, additives should not influence the welding process in a negative way. For example, strong disturbances of the welding arc or deterioration of the mechanical properties of the weld should be avoided. Keeping these selection criteria in mind, a first selection was made. The pre-selected additives are listed in Table 3.1.

The oxides (SiO₂, TiO₂, Fe₂O₃, MgO and Cr₂O₃) are selected recalling the possibility of the formation of negatively charged ions, presumably resulting in arc contraction. The choice
Chapter 3

of the carbonates (Na₂CO₃, K₂CO₃ and CaCO₃) is based on the fact that the cations of the selected carbonates have very low ionization potentials, which is expected to result in a decrease in arc voltage. Finally, the halogenides chosen (NaCl, KCl, CaCl₂ and AlF₃) will influence the arc both by the presence of low ionization potential cations and the possibility of negative ion formation in the cooler regions of the arc.

Table 3.1 Pre-selected additives.

<table>
<thead>
<tr>
<th>additive</th>
<th>selection criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>negative ion formation</td>
</tr>
<tr>
<td>TiO₂</td>
<td>negative ion formation</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>negative ion formation</td>
</tr>
<tr>
<td>MgO</td>
<td>negative ion formation</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>negative ion formation</td>
</tr>
<tr>
<td>Na₂CO₃</td>
<td>low ionization potential cation</td>
</tr>
<tr>
<td>K₂CO₃</td>
<td>low ionization potential cation</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>low ionization potential cation</td>
</tr>
<tr>
<td>NaCl</td>
<td>low ionization potential cation + negative ion formation</td>
</tr>
<tr>
<td>KCl</td>
<td>low ionization potential cation + negative ion formation</td>
</tr>
<tr>
<td>CaCl₂</td>
<td>low ionization potential cation + negative ion formation</td>
</tr>
<tr>
<td>AlF₃</td>
<td>low ionization potential cation + negative ion formation</td>
</tr>
</tbody>
</table>

3.3 Experimental set-up

To investigate the influence of the pre-selected additives on the properties of the welding arc, a number of GTA welding experiments was carried out with standard GTA welding equipment. The experimental set-up is shown in Fig. 3.1. During welding the torch is kept in fixed position, while a travel bench offers the possibility to move the workpiece in horizontal direction with different travel speeds. The torch can be adjusted allowing different arc lengths during welding. In the torch a tungsten electrode, doped with 2% thoria, is placed. As workpiece a 200x200x10 mm mild steel plate (Fe360) is used. To protect the electrode, the arc and the weld pool from the surrounding atmosphere, argon is used as shielding gas. An ESAB DTA 300 welding power supply provides the welding
The influence of additives on the welding arc

current. During welding the arc voltage between torch and workpiece is directly measured, whereas the welding current is measured by means of a shunt. The output of the shunt is subsequently passed on to a welding monitor that in addition provides galvanic shielding, and to a computer. The voltage is divided by two and passed on directly to a computer. The computer controls the total system (travel unit, power supply, measuring system) using Labview as graphical programming language.

Prior to welding, the workpiece is ground and cleaned with acetone. Part of the workpiece is subsequently coated with the additive.

The additives to be studied are supplied in powder form and can not be applied as such to the surface of the steel, as the pressure of the welding arc and the shielding gas will blow the powders away. Therefore, the powders are ground and mixed with acetone into a paste. This paste is painted on the surface of the workpiece, after which the acetone simply evaporates. In this way, a thin, finely grained layer remains behind on the surface, which appears to be sufficiently well adhered to the steel.

To determine the influence of the various additives on the electrical properties of the welding arc, bead-on-plate experiments were carried out. In these experiments the arc travels across the workpiece, which is partly blank and partly covered by the additive to be studied. During welding the arc voltage is measured continuously, whereas the other welding parameters are kept constant. These standard welding conditions are listed in Table 3.2.

<table>
<thead>
<tr>
<th>workpiece material</th>
<th>Fe 360 plate, 250x200x10 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrode material</td>
<td>tungsten, 2% thoria</td>
</tr>
<tr>
<td>electrode diameter</td>
<td>2.4 mm</td>
</tr>
<tr>
<td>electrode top angle</td>
<td>60°</td>
</tr>
<tr>
<td>polarity</td>
<td>electrode negative</td>
</tr>
<tr>
<td>welding current</td>
<td>180 A</td>
</tr>
<tr>
<td>arc length</td>
<td>3 mm</td>
</tr>
<tr>
<td>shielding gas</td>
<td>argon</td>
</tr>
<tr>
<td>shielding gas flow rate</td>
<td>5 l/min</td>
</tr>
<tr>
<td>travel speed</td>
<td>2 mm/s</td>
</tr>
</tbody>
</table>
Fig. 3.1 Experimental set-up.
3.4 Influence of different additives on arc voltage

Using the equipment and the experimental procedure described above, arc voltage measurements were conducted for each of the additives listed in Table 3.1. Under normal circumstances, i.e. without any additive applied, the arc voltage is about 11 V. By coating the workpiece with additives, the arc voltage either increases or decreases. As an example, the voltage as a function of position is plotted for SiO₂ in Fig. 3.2. It can be seen that the arc voltage increases when the arc enters the SiO₂ covered zone and decreases again to the original level when the arc leaves the covered zone. The mean value of the change in arc voltage for the different additives is listed in Table 3.3.

Table 3.3 The mean change in arc voltage due to additives applied.

<table>
<thead>
<tr>
<th>additive</th>
<th>change in voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>1.72 V ± 0.12</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.38 V ± 0.20</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.84 V ± 0.17</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.35 V ± 0.20</td>
</tr>
<tr>
<td>MgO</td>
<td>0.38 V ± 0.20</td>
</tr>
<tr>
<td>K₂CO₃</td>
<td>-0.32 V ± 0.30</td>
</tr>
<tr>
<td>Na₂CO₃</td>
<td>0.16 V ± 0.30</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>0.23 V ± 0.21</td>
</tr>
<tr>
<td>KCl</td>
<td>-0.33 V ± 0.22</td>
</tr>
<tr>
<td>NaCl</td>
<td>0.03 V ± 0.21</td>
</tr>
<tr>
<td>CaCl₂</td>
<td>0.10 V ± 0.22</td>
</tr>
<tr>
<td>AlF₃</td>
<td>0.72 V ± 0.18</td>
</tr>
</tbody>
</table>

The table shows that the measured change in voltage is quite different for the different additives. This is not surprising in view of their different properties, like for example their different ionization and dissociation energy and their different tendency to form positive and/or negative ions.
Chapter 3

In general, the selected chlorides and carbonates tend to influence the welding arc to the smallest extent. Under influence of the high temperatures in the welding arc, carbonates will decompose, resulting in the presence of both the corresponding metal oxides and carbon dioxide. After decomposition of the chlorides and these oxides, metal vapors will be present in the welding arc, which becomes apparent by the emission of light with a wavelength characteristic for the metal, for instance orange light in the case of sodium. Both in the case of carbonates and chlorides a trend can be noticed in the effect on the welding arc, which corresponds with the trend in ionization potential of the metal cations.

![Graph showing voltage versus position](image)

**Fig. 3.2**  Arc voltage versus position plot when welding with the addition of SiO₂.

The influence of the applied oxides appears to be larger than that of the other additives and ranges from a rise in arc voltage of 0.3 V for MgO to 1.7 V for SiO₂. To obtain more insight in the mechanisms causing the change in arc voltage, additional experiments were carried out. In these experiments SiO₂ was used as additive, as this compound exhibits the largest effect on the welding arc.
3.5 The influence of welding conditions on the effect of additives

To study in the influence of additives on arc behavior in more detail, additional experiments were carried out. Firstly, the influence of additive layer thickness was paid attention to. Subsequently, experiments were carried out in which arc length, welding current and travel speed were varied separately, the other welding parameters being kept constant. In all these experiments SiO₂ was used as additive.

3.5.1 The influence of layer thickness

For a good understanding of the effects of additives on arc behavior, it is essential to know to what extent the amount of applied additive per unit surface (i.e. the layer thickness of the used additive) plays a role. Therefore, three experiments were carried out with different layer thicknesses. During welding, voltage measurements were carried out under standard welding conditions, as described in the foregoing. After stabilization of the raised voltage, the welding process was stopped. To determine the amount of SiO₂ present on the workpiece per unit area, SiO₂ was scraped off the unwelded part of the workpiece over a predefined area, after which this amount was weighed. In this way the relation could be established between the amount of SiO₂ per unit surface area and the change in arc voltage. In Fig. 3.3 the results of the experiments are depicted. It appears that with increasing amount of SiO₂, the arc voltage increases and approaches a saturation level.

To quantify the maximum amount of SiO₂ that can enter the arc, first the evaporation rate of SiO₂ was determined. Using gas analysis equipment (Ströhlein Osa-Mat 350), a known amount of SiO₂ was heated for 45 s at 2000 °C. After cooling, the remainder of the SiO₂ was determined. It appears that the evaporation rate at 2000 °C equals about 9.5*10⁻⁴ g cm⁻² s⁻¹.

When welding, continuously new additive covered area is exposed to the arc as illustrated for a travel speed of 2 mm/s in Fig. 3.4. The average arc contact time can be obtained by dividing the total surface area of the weld pool by the new surface area created per unit time. Subsequently, the amount that evaporates can be calculated and compared with the amount that was originally present on top of the weld pool. The results are listed in Table 3.4.
Fig. 3.3  The influence of the amount of SiO₂ present on the workpiece per unit area on the change in arc voltage.

From Table 3.4 it can be concluded that in the case of the thin layer all SiO₂ has been evaporated, whereas in the case of the two other layers only part of the SiO₂ originally present on top of the workpiece surface has been evaporated. This confirms the experimental observation that in the latter two cases molten additive is floating on top of the weld pool.

Because the influence of layer thickness on arc voltage decreases with increasing layer thickness, a thick SiO₂ layer (saturation level) was used in all experiments.
The influence of additives on the welding arc

Fig. 3.4  New surface area (shaded part) that is exposed to the arc per second when welding with a travel speed of 2 mm/s.

Table 3.4  Calculation of the evaporated amount of SiO₂ for the three layer thicknesses.

<table>
<thead>
<tr>
<th>layer thickness</th>
<th>thin</th>
<th>medium</th>
<th>thick</th>
</tr>
</thead>
<tbody>
<tr>
<td>amount SiO₂ present (g/cm²)</td>
<td>0.0008</td>
<td>0.0032</td>
<td>0.0840</td>
</tr>
<tr>
<td>surface area weld pool (cm²)</td>
<td>0.34</td>
<td>0.37</td>
<td>0.29</td>
</tr>
<tr>
<td>Δ area/s (cm²) (see Fig. 3.4)</td>
<td>0.17</td>
<td>0.19</td>
<td>0.12</td>
</tr>
<tr>
<td>contact time (s) (surface area/Δ area)</td>
<td>2.00</td>
<td>1.95</td>
<td>2.42</td>
</tr>
<tr>
<td>evaporated amount(g/cm²) (ev. rate*contact time)</td>
<td>0.0019⁺</td>
<td>0.0018</td>
<td>0.0023</td>
</tr>
</tbody>
</table>

*The actual evaporated amount is 0.0008 g/cm².

3.5.2  The influence of arc length

Bead-on-plate experiments with different arc lengths were carried out both in situations without and with SiO₂ as additive, under otherwise standard welding conditions (Table 3.2). In each situation the arc voltage was continuously measured. It was found that the arc length-arc voltage plot obtained in this way yields a linear relationship. The slope of this line represents the electrical field strength in the arc column, whereas extrapolation to zero arc length yields the sum of the voltage in the anode fall region and that in the cathode fall region. The results of the experiments are shown in Fig. 3.5.
Fig. 3.5  Arc voltage as a function of arc length when welding mild steel with (○) and without SiO₂ (●).

It appears that SiO₂ influences both the electric field strength (the slope of the line changes) and the voltage over the fall regions (the line intersects the y-axis at a different position). Similar measurements were carried out at other values of the welding current, viz. 100 A and 250 A instead of 180 A. It appears that with increasing welding current the difference between welding without and with SiO₂ decreases. For each situation the electric field strength in the arc column and the total voltage fall over the fall regions were determined. The overall results are shown in Fig. 3.6 and summarized in Table 3.5.

It can be noticed that the ratio influence-on-electric-field-strength to influence-on-voltage-in-fall-regions changes with increasing welding current. As an example the values for arc length 3 mm are considered. At 100 A, an increase in total arc voltage of 21% is reached. Of this increase 33% is caused by the change in electric field strength and 67% by the raise in fall region voltage. At 180 A the total increase is 12%, of which 31% is due to the change in electric field strength and 69% to the change in the voltage over the fall region. In the case of 250 A, the arc voltage increases with only 5%, of which 15% is caused by the change in electric field strength and 85% by the raise of voltage in the fall regions. Thus,
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with increasing welding current the effect of SiO₂ on the arc column decreases continuously, until the change in arc voltage can be ascribed almost completely to a change in voltage drop in the fall regions.

![Chart showing the influence of arc column and fall regions on arc voltage with welding current as 100 A, 180 A, and 250 A.]

Fig. 3.6 The change in arc voltage at different welding currents when using SiO₂ as an additive.

Table 3.5 The change in electric field strength (arc column) and voltage in the fall regions at different welding currents.

<table>
<thead>
<tr>
<th>current (A)</th>
<th>Δ E (V/m)</th>
<th>Δ (Vₑ+Vₑ) (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>170</td>
<td>1.4</td>
</tr>
<tr>
<td>180</td>
<td>170</td>
<td>0.9</td>
</tr>
<tr>
<td>250</td>
<td>10</td>
<td>0.6</td>
</tr>
</tbody>
</table>

3.5.3 The influence of welding current

As shown in the foregoing, the welding current has an important influence on the effect of SiO₂ on the arc voltage. To further explore the effect of welding current, bead-on-plate experiments were carried out with the welding current varying from 100 to 300 A in steps
of 50 A. The results are depicted in Fig. 3.7 and show a decreasing effect of SiO₂ on the arc voltage with increasing welding current. Eventually, the effect disappears above 300 A. This is consistent with the results obtained by Kazakov [3.26], researching the efficiency of activating fluxes.

![Graph showing the relationship between voltage and welding current](image)

**Fig. 3.7** Arc voltage as a function of welding current when welding mild steel with (o) and without SiO₂ (●).

### 3.5.4 The influence of travel speed

Experiments were also carried out with the travel speed varying from 1 to 5 mm/s. The results are depicted in Fig. 3.8. As expected, the arc voltage does not change with increasing travel speed when welding without SiO₂. When welding with SiO₂, however, it appears that the arc voltage increases with increasing travel speed. Extrapolation of the data points to zero travel speed yields a voltage difference of about 0.7 V. This indicates that the effect of SiO₂ persists under static welding conditions.
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Fig. 3.8 Arc voltage as a function of travel speed when welding mild steel with (○) and without SiO₂ (●).

3.6 Determination of arc shape by photography

Attempts were also made to visualize the effects of additions on the arc by taking photographs of the arc during welding. First photographs were taken in the direction parallel to the welding direction under standard welding conditions (Table 3.2) without and with SiO₂ as additive. Typical pictures obtained are shown in Fig. 3.9. It appears clearly that in the case of welding with SiO₂ arc contraction occurs. As stated above, this phenomenon suggests that negative ion formation takes place, resulting in the observed increase in arc voltage.

Photographs of the arc were also taken in the direction perpendicular to the welding direction without and with SiO₂. The results are shown in Fig. 3.10. It can be noticed that in the case of welding across SiO₂, the position of the arc deviates from that when welding on blank plate. In fact, the arc remains behind with respect to the welding direction, in other words: arc trailing occurs. This obviously results in a longer effective arc length, which in turn leads to a larger voltage drop over the arc column. Both arc contraction and negative ion formation will be discussed in more detail in section 3.8.
Fig. 3.9  Photographs of the welding arc in the travel direction: top: without SiO$_2$; bottom: with SiO$_2$. 
Fig. 3.10 Photographs of the welding arc perpendicular to the travel direction: top: without SiO₂; bottom: with SiO₂.
3.7 Spectroscopic measurements

In an attempt to obtain more information about the particles present in the arc, qualitative spectroscopic measurements were carried out. Use was made of a Perkin Elmer Plasma II spectroscope. The situation is schematically shown in Fig. 3.11. A focus lens collects the light that is emitted by the arc plasma. Subsequently, the light is transferred to a monochromator through a glass fiber cable. A photon multiplier detector transforms the light signal into an electric signal, which is passed to a computer and transformed to an emission light profile by a computer program. The specifications of the monochromator are listed in Table 3.6.

![Diagram of spectroscopic measurements]

Fig. 3.11 Schematic set-up for spectroscopic measurements.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>focal length</td>
<td>1 m</td>
</tr>
<tr>
<td>resolution</td>
<td>0.018 nm</td>
</tr>
<tr>
<td>linear dispersion</td>
<td>0.527 nm/mm</td>
</tr>
<tr>
<td>grating</td>
<td>1800 lines/mm</td>
</tr>
</tbody>
</table>

Table 3.6 Specifications of the monochromator.
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Table 3.7  Selected spectral atom lines of argon, silicon and iron [3.27].

<table>
<thead>
<tr>
<th>Line</th>
<th>wavelength $\lambda$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ArII</td>
<td>480.6017</td>
</tr>
<tr>
<td>SiII</td>
<td>386.2595</td>
</tr>
<tr>
<td>FeII</td>
<td>259.1543</td>
</tr>
</tbody>
</table>

For the spectral analysis, three lines were selected. The characteristics of these lines are listed in Table 3.7. The intensities of the selected lines were measured on two different positions in the welding arc as shown in Fig. 3.12, both during welding on blank plate and during welding across SiO$_2$. Welding was performed under standard welding conditions.

![Diagram showing spectroscopic measurements on two spots in the welding arc.](image)

Fig. 3.12  Spectroscopic measurements on two spots in the welding arc.

It was found that, when welding on blank plate, the ArII and FeII lines can be detected on both spots, whereas no SiII line is observed. When entering the region covered with SiO$_2$, the intensity of the FeII line strongly decreases, while the SiII line becomes clearly visible. The intensity of the ArII line remains at about the same level. These observations are valid for both positions. On the basis of these observations it can be concluded that, when using SiO$_2$ as additive, Si enters the welding arc and partly replaces Fe. Furthermore, it appears that the width at half height of the ArII line is not affected by SiO$_2$ addition. This means that no change in electron density can be detected in this experiment. Since silicon enters the arc, it can be expected that oxygen is present as well. This was confirmed by spectroscopic measurements of an oxygen line.
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3.8 Discussion

As already stated in the introduction of this chapter, additives can influence the welding arc in various ways.

In the case of introducing SiO₂ into the welding arc, chemical reactions may occur like dissociation, recombination and ionization, the latter giving rise to the generation of either positive or negative ions. The reactions that are most likely to occur are:

\[
\begin{align*}
\text{SiO}_2 & \rightleftharpoons \text{SiO} + \text{O} \\
\text{SiO} & \rightleftharpoons \text{Si} + \text{O} \\
2 \text{O} & \rightleftharpoons \text{O}_2 \\
\text{Si} & \rightleftharpoons \text{Si}^+ + \text{e}^- \\
\text{SiO} + \text{e}^- & \rightleftharpoons \text{SiO}
\end{align*}
\]

These reactions lead to products which may have a specific effect on the properties of the arc and, consequently, on arc voltage. Furthermore, the energy distribution in the arc could be altered as a result of these reactions.

It was shown in the foregoing that apart from these effects, arc trailing also plays a role. All in all, four phenomena may play a role when introducing SiO₂ into the welding arc:
- arc trailing;
- dissociation;
- positive ion formation;
- negative ion formation.

In this section, these phenomena are discussed and an attempt is made to decide to which extent they are relevant to explain the experimental results.

3.8.1 Arc trailing

In previous sections it was concluded that during welding across SiO₂ arc trailing occurs. Arc trailing can be defined as the incapability of the arc root to keep up with the travelling electrode above it. This is presumably due to the molten SiO₂ layer present at the front side
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of the weld pool, which resists movement of the arc root. Clearly, arc trailing will result in a longer effective arc length, hence causing a raise in arc voltage, as illustrated by Fig. 3.13.

In Fig. 3.8, it was shown that the effect of SiO₂ on arc voltage increases with increasing travel speed. At least part of this effect is due to trailing, since it is to be expected that the trailing effect increases with increasing travel speed, resulting in a larger deviation from the normal situation, and hence in a larger effective arc length. Photographs of the welding arc taken at different travel speeds show that this expectation is justified.

![Diagram](image-url)

Fig. 3.13  Schematic presentation of arc trailing and its influence on arc length.
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Assuming that arc trailing does not influence the fall regions of the welding arc and only affects the arc column, its influence on arc voltage over the column can be estimated by making use of the equation:

\[
\Delta V_{\text{trail}} = \Delta l \cdot E \tag{3-1}
\]

in which \(\Delta V_{\text{trail}}\) represents the change in arc voltage due to trailing, \(\Delta l\) the effective arc length minus nominal arc length and \(E\) the electric field strength of the arc column.

Taking for \(\Delta l\) values obtained from the photographs and for \(E\) the value presented in section 3.5.2, the change in arc voltage due to arc trailing can easily be obtained. In Table 3.8, the calculated \(\Delta V\) values are given together with the measured \(\Delta V\) values for two different travel speeds.

When comparing the measured and the calculated values of \(\Delta V\), it can be concluded that arc trailing can only account for a small part (ca. 10%) of the observed change in arc voltage due to SiO₂ addition, depending on the welding parameters used.

Table 3.8 The experimentally obtained change in column voltage (\(\Delta V_{\text{col}}\)) and the calculated change in column voltage due to trailing (\(\Delta V_{\text{col, cal}}\)).

<table>
<thead>
<tr>
<th>travel speed</th>
<th>(\Delta V_{\text{tot}}) (V)</th>
<th>(\Delta V_{\text{col}}) (V)</th>
<th>(\Delta V_{\text{col, cal}}) (V)</th>
<th>(\Delta V_{\text{col, cal}}/\Delta V_{\text{tot}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 mm/s</td>
<td>1.9</td>
<td>0.98</td>
<td>0.14</td>
<td>0.073</td>
</tr>
<tr>
<td>4 mm/s</td>
<td>3.3</td>
<td>2.21</td>
<td>0.40</td>
<td>0.122</td>
</tr>
</tbody>
</table>

3.8.2 Dissociation

It is well known that dissociation of molecules in an arc plasma may give rise to a significant modification in the heat conductivity of the plasma, which in turn may lead to a change in the temperature distribution and the current density distribution in the arc. For example, Lambert [3.28] used various gas mixtures and found that, when welding with the same welding current, the arc voltage increased in the order Ar, Ar-5 vol.%N₂ and Ar-5 vol.%H₂. It may well be possible that similar effects also play a role when welding with SiO₂ as additive, since in this case also dissociation reactions take place (see above). It is obvious that this effect plays only a role when a significant amount of SiO₂ is present in the arc.

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The volume percentage of SiO$_2$ in the welding arc can be estimated by calculating the inflow of both argon and SiO$_2$ into the arc per unit time and assuming that once in the arc the two components mix immediately (see Fig. 3.14). Taking for the inflow rate of argon the value 0.02 l/s (~25 % of the total flow rate) and for the inflow rate of SiO$_2$ the value 2.8*10$^4$ l/s (see section 3.5.1), this results in a SiO$_2$ volume fraction in the order of 1%.

![Diagram](image)

**Fig. 3.14** Schematic situation used as the basis to estimate the volume fraction of SiO$_2$ in the arc plasma.

In the present situation the following dissociation reaction should be considered (dissociation energies were calculated by means of the enthalpy of formation values):

\[
\begin{align*}
\text{SiO}_2 & \rightarrow \text{SiO} + \text{O} \quad E_d = 4.9 \text{ eV} \\
\text{SiO} & \rightarrow \text{Si} + \text{O} \quad E_d = 8.6 \text{ eV}
\end{align*}
\]

The dissociation energy of SiO$_2$ is similar to that of hydrogen ($E_d = 4.5$ eV), while the dissociation energy of SiO is comparable with that of nitrogen ($E_d = 9.7$ eV). The change in arc voltage due to the presence of 1 vol.% of hydrogen and nitrogen in the welding arc is about 0.25 V and ~0 V [3.29], respectively. In view of this, it can be assumed that the dissociation of SiO$_2$ will cause a voltage change of maximum 0.25 V at standard welding conditions, whereas the dissociation of SiO will not influence the arc voltage significantly. Hence, the complete dissociation of SiO$_2$ can account for only a small part (about 10%) of the total effect.
3.8.3 Positive ion formation

Over the years, many attempts have been made to develop methods for calculating the electrical conductivity of ionized gases. Overviews are given by Sherman [3.30] and by Lin et al. [3.31]. Two different approaches were used to derive equations for calculating the conductivity:

- the gas is slightly ionized [3.32];
- the gas is fully ionized [3.33, 3.34].

With the help of the equations derived for slightly and fully ionized gases, Lin et al. [3.31] developed a model for calculating the conductivity of a gas of arbitrary degree of ionization, which reflects the situation in electric welding arcs, as was argued by Dunn and Eagar [3.35]. On the basis of this work it is possible to calculate the electrical conductivity of the plasma in the arc column, as is shown in Appendix A.2.

Fig. 3.15 Electric conductivity of argon plasma seeded with Fe and Si.
It appears that small amounts of iron strongly influence the conductivity of the pure argon plasma (Fig. 3.15), as was also stated by Glickstein [3.8]. When welding steel, however, the plasma will not be a binary argon-iron plasma, but a mixture of argon with iron, manganese and other alloying elements. To estimate the influence of small additions of Si (generated by the dissociation of SiO₂) on the conductivity of the welding arc, the conductivity of a ternary gas mixture (Ar+10% Fe +1% Si) was calculated. The results are shown in Fig. 3.15. It appears that the conductivity of this ternary gas mixture hardly differs from the conductivity of the argon-iron plasma. If there is any influence this will be noticed mostly at lower temperatures, thus at the anode side of the welding arc.

The results clearly indicate that the presence of silicon atoms/ions will not have a significant influence on the electric behavior of the arc column, and, hence, will not contribute to the observed change in arc voltage.

When considering the effect of positive silicon ions on the fall regions, it should be recalled that no Local Thermodynamic Equilibrium exists in these regions. As a consequence, the method followed above cannot be used to theoretically predict the effect of positive ions on the electrical properties of these regions. Instead of this, use must be made of Poisson’s Law, as discussed in Appendix A.3.1. This approach is based on a comparison between the electric field strength with and without the presence of positive ions. As an example, the influence of iron and silicon ions on the electric field strength in the anode fall region is depicted in Fig. 3.16. In the anode fall region, the ratio of the ion current density and the electron current density, \( j_i/j_e \), will be between zero and one. Again it must be realized that the influence of Si⁺-ions on the arc should be compared with the situation of an arc with Fe⁺-ions present. As can be concluded from the figure, replacing Fe⁺ ions by Si⁺ ions leads to a decrease in electrical field strength, and hence in voltage fall. However, \( j_i/j_e \) is close to zero in the anode fall region, which implies that the influence on arc voltage will be negligibly small.

In the case of the cathode fall region, it can be shown in a similar way that the presence of Si⁺-ions does not have a substantial influence on the arc voltage (see Appendix A.3.2).
3.8.4 Negative ion formation

It was shown in the foregoing that the formation of positive Si\(^+\) ions does not lead to major changes in the electric behavior of the arc. This could be expected because SiO\(_2\) addition results in partial replacement of the original positive ions (Fe\(^+\)) by other positive ions (Si\(^+\)), which does not influence the space charge. However, the presence of SiO\(_2\) in the arc zone will also give rise to negative ion formation, as will be explained below.

In the core of the arc column, the temperature is high enough to cause complete dissociation of the SiO\(_2\) molecules (see section 3.8.2). In the cooler regions, however, the dissociation is incomplete and SiO molecules will be present. Since SiO has a positive electron affinity (~1.5 eV), the SiO molecules tend to capture electrons, forming negative SiO\(^-\) ions. This electron capture will locally (especially in the outer part of the arc, where the temperature is relatively low) cause a decrease in the electron current density, resulting in constriction of the arc (Fig. 3.17). Because the welding current is fixed, the arc voltage will increase.
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Fig. 3.17  Schematic presentation of arc constriction due to negative ion formation in the outer region of the welding arc.

The influence of negatively charged particles on the anode fall region can be approached in the same way as was done for positive ions. The method is presented in Appendix B.3.1. It appears that a very small number of negative ions can have a large impact on the electric field strength in the anode fall region, as is illustrated in Fig. 3.18.

In Appendix B.3.2, the influence of negative ions on the cathode fall region is discussed. It appears that the presence of a small number of negatively charged ions does not influence the cathode fall voltage noticeably.
Fig. 3.18  Influence of SiO⁻⁻-ions on the electric field strength in the anode fall region.

On the basis of the foregoing it can be concluded that the influence of SiO₂ on the electrical properties of the arc is caused by different phenomena. An important part of the total effect can be ascribed to arc contraction caused by negative ion formation. Furthermore, it appears that both arc trailing and dissociation play a modest role, while the influence of positive ion formation is negligibly small.

To further evaluate this conclusion, it is interesting to consider the influence of the welding parameters on each of the three phenomena playing a role. This leads to the following qualitative observations, which are summarized in Table 3.9.

Table 3.9  The qualitative effect of welding parameters on the three different mechanisms.

<table>
<thead>
<tr>
<th>mechanism</th>
<th>welding current</th>
<th>travel speed</th>
<th>arc length</th>
</tr>
</thead>
<tbody>
<tr>
<td>negative ion formation and arc contraction</td>
<td>↓</td>
<td>↑</td>
<td>~</td>
</tr>
<tr>
<td>dissociation</td>
<td>↓</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>arc trailing</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>total effect</td>
<td>↓↓</td>
<td>↑↑</td>
<td>↑</td>
</tr>
</tbody>
</table>
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A higher welding current leads in general to a higher temperature of the welding arc. Relatively speaking, the probability of negative ion formation will decrease and, hence, the tendency of the welding arc to constrict will be smaller. In addition, the increased plasma vortex leads to a smaller number of SiO₂ molecules in the welding zone. However, negative ion formation will be promoted by an increase in travel speed, due to the decreasing heat input. Increasing the arc length will hardly influence arc contraction.

An increase in heat input will cause a relative decrease of the influence of dissociation, due to higher temperatures in the welding arc. In other words, the role of dissociation will decrease with increasing welding current and arc length, while the effect will increase with travel speed.

The effect of arc trailing will decrease with welding current, due to the increased stiffness of the welding arc. In addition, the increased plasma flow will promote the removal of part of the SiO₂ from the arc zone, leading to a decrease in volume percentage. Increasing the travel speed leads to an increased effect, as demonstrated before by photographs of the welding arc during welding, while with increasing arc length, the effect of arc trailing will slightly increase.

When comparing the foregoing observations with the experimental results, it appears that theory and practice are in reasonable agreement: the effect of SiO₂ on the arc voltage disappears gradually with increasing welding current, becomes more apparent with increasing travel speed and increases slightly with increasing arc length.

3.9 Conclusions

This chapter deals with the influence of additives on the welding arc. A number of additives were preselected on the basis of their expected influence on arc behavior. It appears that all preselected additives influence the arc to a different degree. Oxides and fluorides seem to have the largest effect. By carrying out further experiments with SiO₂, the influence of this additive on the welding arc under different process conditions was mapped. The following trends were observed:
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- SiO₂ influences both the electric field strength in the arc column and the voltage drop in the anode and cathode fall region;
- the influence of SiO₂ on the welding arc increases with increasing arc length;
- the influence of SiO₂ on the welding arc decreases with increasing welding current;
- the influence of SiO₂ on the welding arc increases with increasing travel speed.

Based on theoretical considerations, an attempt was made to explain the experimental results in terms of different phenomena that can play a role: arc trailing, dissociation, positive ion formation and arc contraction by negative ion formation. It was concluded that:

- arc contraction by negative ion formation is the dominant mechanism and has the largest influence on arc voltage;
- dissociation can account only for a small part (about 10%) of the change in arc voltage;
- arc trailing also contributes only for a small part (ca. 10%) to the change in arc voltage;
- positive ion formation does not or hardly contribute to the change in arc voltage.
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WRC Bulletin, no. 357, September 1990, 1-21
THE INFLUENCE OF ADDITIVES ON THE WELD POOL

In the previous chapter the influence of additives on the welding arc was discussed from both a theoretical and a practical point of view. In this discussion, no attention was paid to the consequences of the use of these additives with respect to the weld pool. When reviewing literature, it appears that numerous articles have been published concerning the effect of minor elements, additives and fluxes on the weld pool. The study of minor element effects and especially their effect on Marangoni flow, was initiated by Heiple and Rooper [4.1-4.3] and the research in this area is still a continuing story [4.4, 4.5]. The effect of additives and fluxes on the weld pool is particularly focused on the modified GTA welding process, ATIG [4.6]. This process has the specific advantage that increased weld penetration is achieved by using certain types of fluxes. Although a great deal of research has been carried out in this area, few researchers appear to have found a satisfying explanation for the enhanced penetration in ATIG welding.

In this chapter the influence of additives on the weld pool will be addressed. Focus will be on a number of additives, which were also used in the arc study presented in the previous
chapter. Specific attention will be paid to the influence of these additives on the shape and size of the weld pool under various welding conditions. Furthermore, the microstructure and the mechanical properties of welds made with and without additives will be compared and discussed. Finally, an attempt will be made to explain the results in terms of heat input, arc-workpiece contact area and weld pool flow.

4.1 Experimental conditions

To determine the influence of additives on the weld pool, bead-on-plate experiments were carried out. As base material Fe 360 plate was used. The composition of the base material is listed in Table 4.1.

<table>
<thead>
<tr>
<th>Element</th>
<th>Mn</th>
<th>Cu</th>
<th>Si</th>
<th>C</th>
<th>Co</th>
<th>Cr</th>
<th>S</th>
<th>P</th>
<th>O</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt%</td>
<td>0.65</td>
<td>0.26</td>
<td>0.25</td>
<td>0.10</td>
<td>0.08</td>
<td>0.08</td>
<td>0.041</td>
<td>0.01</td>
<td>0.013</td>
<td>bal.</td>
</tr>
</tbody>
</table>

The concentration of the elements S, C and O was measured with gas analysis equipment (Ströhlein OSA-Mat), while the concentration of the other elements was determined with X-ray fluorescence spectroscopy (Philips PW 1480). The experiments were carried out using a standard GTA welding set-up. The standard welding conditions and additives used are listed in Table 4.2 and Table 4.3, respectively.

<table>
<thead>
<tr>
<th>workpiece material</th>
<th>Fe 360 plate (250x200x10 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrode</td>
<td>W (2% ThO₂), 2.4 mm, tip angle 60°</td>
</tr>
<tr>
<td>polarity</td>
<td>electrode negative</td>
</tr>
<tr>
<td>power supply</td>
<td>ESAB DTA 300</td>
</tr>
<tr>
<td>shielding gas</td>
<td>Ar, 5 l/min</td>
</tr>
<tr>
<td>welding current</td>
<td>180 A</td>
</tr>
<tr>
<td>arc length</td>
<td>3 mm</td>
</tr>
<tr>
<td>travel speed</td>
<td>2 mm/s</td>
</tr>
</tbody>
</table>
After welding, transverse cross-sections were made of welds produced without and with additive. Subsequently, the samples were ground, polished and etched with Nital (2%). Of each cross-section the depth (D), width (W), depth-to-width ratio (D/W) and the surface area of the weld was determined using optical microscopy (Jenavert microscope in combination with Leica Imaging Systems). To further explore the influence of additives on the weld pool formation during GTA welding, additional experiments were carried out using varying process parameters with SiO₂ as additive.

Optical microscopy (Neophot 3) was used to examine the microstructure of the welds. The mechanical properties of the welds were measured by means of Vickers hardness testing (Leitz) and by tensile testing (Instron 50kN).

<table>
<thead>
<tr>
<th>Additive</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>98%</td>
</tr>
<tr>
<td>TiO₂</td>
<td>98%</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>98%</td>
</tr>
<tr>
<td>Na₂CO₃</td>
<td>98%</td>
</tr>
<tr>
<td>K₂CO₃</td>
<td>98%</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>98%</td>
</tr>
</tbody>
</table>

**4.2 Results**

**4.2.1 General observations**

To obtain insight in the influences that additives have on the weld pool, experiments were carried out without and with the different additives under standard welding conditions. Some of the results are presented in Fig. 4.1. It appears that most additives give rise to a significant raise in depth-to-width (D/W) ratio. Oxides tend to have the largest influence on the D/W ratio. By far the largest effect on the D/W ratio was observed in the case of SiO₂ as additive. In Fig. 4.2 a typical example of cross-sections of welds obtained with and without SiO₂ is shown.
To obtain more insight in the phenomena playing a role in weld pool formation in the presence of additives, additional experiments were carried out, in which the layer thickness, the travel speed, the welding current and the arc length were varied separately, the other welding parameters being kept constant. These experiments focused on SiO₂ as additive, as this compound has the largest influence on both the arc (see Chapter 3) and the weld pool.

![Image](image_url)

Fig. 4.1 Depth-to-width ratio of welds produced without and with different additives.

4.2.2 The influence of layer thickness

Before carrying out bead-on-plate experiments with varying welding parameters, it is important to know to what extent the layer thickness of the additive plays a role. Three experiments were carried out under standard welding conditions, in which SiO₂ layers of different thickness were applied on the surface of the workpiece. The amount of SiO₂ originally present at the surface of the workpiece was determined as described in section 3.5.1. Subsequently, transverse cross-sections were prepared after which the size and shape of the different welds were determined. The results are depicted in Fig. 4.3. It appears that the depth-to-width ratio increases about linearly with increasing amount of SiO₂ on the workpiece.
The influence of additives on the weld pool

Fig. 4.2 Cross-sections (dark field) of welds obtained with (a) and without (b) SiO₂.
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![Graph showing D/W ratio vs SiO₂ (g/cm²)]

Fig. 4.3  The influence of the amount of SiO₂ applied on the surface of the workpiece on the depth-to-width ratio of the weld.

4.2.3  The influence of welding current

Bead-on-plate experiments were carried out with and without SiO₂, in which the current was varied from 100 to 300 A in steps of 50 A, whereas the other welding parameters were kept constant at their standard value. The results of the experiments with blank plate are shown in Fig. 4.4a. It can be seen that with increasing welding current, the length, width and depth of the weld pool increase.

When comparing these results with those obtained when welding with SiO₂ (Fig. 4.4b), two major differences can be noticed: in the presence of SiO₂ the change in weld pool length with arc current is more rapid, while the change in weld pool width is smaller. In addition, the weld pool depth appears to increase somewhat faster with increasing welding current.

It is important to observe that at higher currents, the effect of SiO₂ on the arc voltage gradually disappears (see Chapter 3), while this is apparently not the case with the influence of SiO₂ on the weld pool.
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Fig. 4.4  Weld pool size (width W, depth D and length L) as a function of welding current: a) welding without additive; b) welding with SiO₂ as additive.
Fig. 4.5  Weld pool size as a function of travel speed: a) welding without additive; b) welding with SiO₂ as additive.
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Fig. 4.6  Weld pool size as a function of arc length: a) welding without additive; b) welding with SiO₂ as additive.
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4.2.4 The influence of travel speed

To determine the influence of travel speed on the weld pool formation in the presence as well as in the absence of SiO₂, GTA welding experiments were carried out at travel speeds varying between 1 and 5 mm/s in steps of 1 mm/s. In Fig. 4.5a the dimensions of welds obtained by welding without SiO₂ at different travel speed are presented. It appears that the length, width and depth of the weld pool all decrease with increasing travel speed. Similar changes are observed in the case of welding with SiO₂ (Fig. 4.5b). However, the weld pool width appears to decrease considerably faster with increasing travel speed, whereas the weld pool length changes at a somewhat smaller rate in comparison with weld pools obtained without SiO₂. In all cases the depth of the weld obtained with SiO₂ is larger than the depth of the blank weld.

4.2.5 The influence of arc length

To complete the parameter study, experiments were also carried out with varying arc length without and with SiO₂. The arc length was varied between 1 and 5 mm in steps of 1 mm. As shown in Fig. 4.6a, the width and the length of the blank weld are hardly influenced by the arc length, while the depth of the weld pool decreases slightly with increasing arc length.

The values of the weld pool dimensions found in the case of welding with SiO₂ are shown in Fig. 4.6b. It appears that under these conditions the length of the weld pool increases with increasing arc length, while the values of the width of the welds are smaller than those obtained without SiO₂. The depth of the welds seems to be independent of arc length and is larger than the depth of the blank welds in all cases.

4.2.6 The depth-to-width ratio

Since in welding practice the D/W ratio is more important than the separate dimensions of the weld pool, it is appropriate to translate the results presented in the foregoing sections in terms of this ratio. This leads to Fig. 4.7, in which the D/W ratio is plotted as a function of welding current, travel speed and arc length both for welding without and with SiO₂ as additive. In this figure it can be seen that, as expected, in all cases the D/W ratio of welds obtained with SiO₂ is larger than that of the welds obtained without SiO₂.
Fig. 4.7 Depth-to-width ratio as a function of welding current, travel speed and arc length for welds obtained without (○) and with (●) SiO₂.
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4.3 Evaluation of the results

In the foregoing, the results of the experiments aimed at determining the effect of additives, and in particular SiO₂, on the formation of the weld pool were presented. On the basis of visual observations and relevant literature it was found that different phenomena have to be considered when trying to explain the observed results, the two most important phenomena being:

- the change in size and shape of the contact area between arc and weld pool caused by the presence of molten additive on top of the weld pool;
- the change in flow of the molten metal, due to changes in the concentration of surface active elements in the weld metal and/or changes in the temperature gradient along the surface of the weld pool.

In this section, the obtained results will be discussed in terms of these two phenomena.

4.3.1 Contact area between arc and weld pool

During welding, the size and shape of the weld pool is dependent on the arc shape and the heat flow in the workpiece. An appropriate way to describe the heat flow in the workpiece is to calculate the heat balance in each volume element of the material involved in the welding process. The heat balance can be expressed as:

\[ \rho c \frac{dT}{dt} = \nabla[k\nabla T] - \rho c v \nabla T + q \]  \hspace{1cm} (4-1)

in which \( \rho \), \( c \), \( T \), \( t \), \( k \), \( v \) and \( q \) are the specific mass, specific heat, temperature, time, heat conductivity, travel speed and heat production in a unit volume per unit time, respectively. The term on the left hand side of the equation represents the temperature change per unit time in a volume element, while the first term on the right hand side describes the temperature change due to thermal diffusion and the second term the temperature change due to convection. The third term stands for the heat production in the specific volume element per unit time.
The influence of additives on the weld pool

When introducing moving coordinates and applying some simplifications (as suggested by Rosenthal [4.7]) this equation can be solved for both 2-dimensional (2-D) and 3-dimensional (3-D) situations, resulting in the equations:

\[ T(t, r) - T_0 = \frac{Q}{2dk} \sqrt{\frac{\alpha}{\pi t}} \exp\left(-\frac{r^2}{4\alpha t}\right) \]  \hspace{1cm} (4-2a)

\[ T(t, r) - T_0 = \frac{Q}{2\pi kt} \exp\left(-\frac{r^2}{4\alpha t}\right) \]  \hspace{1cm} (4-2b)

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

When considering the arc as a point like heat source (one of the simplifications suggested by Rosenthal), and assuming the heat flow in the workpiece to be 3-D, the isotherms in the transverse cross-section of the workpiece will be circular-concentric, as illustrated in Fig. 4.8. In this case a weld pool will be formed, which is semicircular in cross-section and which will have a depth-to-width ratio of 0.5.

![Fig. 4.8 Isotherms in the transverse cross-section of the workpiece in the case of a point like heat source.](image-url)
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Under real welding conditions, the heat source will not be point like, but will have the form of the contact area between arc and workpiece. As a consequence, the depth-to-width ratio of the weld pool will be smaller than 0.5. The larger the contact area, the smaller the depth-to-width ratio. The contact area is dependent on the welding parameters, in particular on welding current and arc length, but could also be influenced by external factors. For example, in plasma arc welding, the arc and, hence, the arc-workpiece contact area are physically constricted by a water-cooled ring and an additional inert gas flow. In a similar way, additives can chemically constrict the arc column zone as described in the previous chapter. Furthermore, additives can physically constrict the contact area between arc and workpiece by covering part of the weld pool and in this way force the arc to approach the point source situation.

In the following, an attempt is made to qualitatively explain the influence of the welding parameters on the effect of SiO₂ on weld pool formation (see section 4.2) in terms of arc root constriction.

Influence of welding current

During GTA welding, the welding current determines the weld pool shape to an important extent. Initially, when raising the welding current from zero value, the base material will be able to transfer the supplied heat by heat conduction without melting. Depending on the physical properties of the base material and the other welding parameters used, at a certain moment a weld pool will be formed. Raising the welding current from there on to higher values will lead to an almost linear increase in weld pool size [3.8-3.10].

The experimental results show indeed that the weld pool grows about linearly in all directions with increasing welding current (Fig. 4.4). This is due to the linearly increasing heat input when welding with higher welding currents. In addition, the width and length of the weld pool increase due to the enlarging anode root at increasing welding currents.

In the case of welding with SiO₂, molten SiO₂ is floating on top of the weld pool. As a consequence, the ability of the anode root to broaden will be reduced resulting in a narrower and longer weld pool than in case of welding without SiO₂. This effect becomes more apparent with increasing arc current.

Influence of travel speed

When increasing the travel speed during welding, it can be expected that the size of the weld pool decreases [4.8-4.10]. This is obviously due to the fact that the heat input is
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inversely proportional to the travel speed. Furthermore, the shape of the weld pool in top view will become more and more elliptic. Eventually, it will change from elliptic to drop shaped, because the heat flow in backward direction will continuously decrease. Thus, when welding blank plate the length, width and depth of the weld pool will decrease with increasing travel speed (Fig. 4.5). It appears that especially the temperature gradient at the backside of the weld pool will be influenced by the travel speed. As a consequence, the decreasing heat input particularly affects the weld pool length.

The observed changes induced by the presence of SiO₂ can be understood by realizing that increasing the travel speed results in a reduction of the ability of the arc to burn the SiO₂ away. This leads to a larger decrease in weld pool width in comparison with welds without SiO₂. This phenomenon forces the weld pool length to decrease much less rapidly.

Influence of arc length

As has been shown in the previous chapter, the arc voltage increases with increasing arc length. However, the dimensions of the weld pool pass through a maximum under these conditions [3.8-3.10]. This can be explained by the fact that with increasing arc length, the heat is passed through an increasingly larger area of the workpiece. As long as the energy density is large enough, the molten area will increase simultaneously. At a certain critical value, however, the energy density at the edges of the arc will become insufficiently large to cause melting, resulting in a decrease of weld pool size. This predicted behavior was confirmed by experiments carried out on blank plate (see section 4.2).

When welding with SiO₂, the molten SiO₂ changes the contact area of the welding arc with the workpiece from circular to elliptic.

4.3.2 Weld pool flow

On the basis of the foregoing it might be concluded that the constriction of the arc-weld pool contact area plays an important role. However, when considering the factors that influence weld pool formation, not only the size of this contact area is of importance, but also convection of the liquid metal in the weld pool.

In Chapter 2, the different forces determining the flow in the weld pool were discussed. Roughly speaking, four elementary forces play a role: the electromagnetic force (Lorentz), the thermocapillary force (Marangoni), the aerodynamic drag force (plasma jet) and the gravitational force (buoyancy). Under normal welding conditions, the influence of these
four forces on the weld pool is suggested to be: Marangoni > Lorentz > plasma jet > buoyancy [4.11].
In the following, only the two most important forces (Marangoni force and Lorentz force) will be taken into account.

Surface tension
When considering Marangoni flow, it can be argued that this flow will be most easily influenced by additives. The key parameter determining the Marangoni flow the surface tension of the liquid metal, which is dependent on the eventual presence of surface-active elements like oxygen and the temperature gradient along the weld pool surface.
To determine whether the Marangoni flow is influenced by the presence of SiO$_2$, first the chemical composition of welds produced with and without SiO$_2$ was determined, using the equipment described in section 4.1. The results are listed in Table 4.4.

<table>
<thead>
<tr>
<th>Element (wt. %)</th>
<th>base material</th>
<th>weld obtained without SiO$_2$</th>
<th>weld obtained with SiO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>0.32</td>
<td>0.35</td>
<td>0.43</td>
</tr>
<tr>
<td>Mn</td>
<td>0.65</td>
<td>0.65</td>
<td>0.58</td>
</tr>
<tr>
<td>Ni</td>
<td>0.10</td>
<td>0.09</td>
<td>0.10</td>
</tr>
<tr>
<td>Cu</td>
<td>0.26</td>
<td>0.23</td>
<td>0.22</td>
</tr>
<tr>
<td>Cr</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>O</td>
<td>0.013</td>
<td>0.017</td>
<td>0.038</td>
</tr>
<tr>
<td>Fe</td>
<td>balance</td>
<td>balance</td>
<td>balance</td>
</tr>
</tbody>
</table>

It appears that both the oxygen content and the silicon content of the weld metal increase when welding with SiO$_2$.
It is to be expected that the increased oxygen content will lead to a change in surface tension and, hence, in a change in Marangoni flow.
In 1988, Keene reviewed a large amount of data concerning the surface tension of iron and its binary alloys [4.12]. The data of the Fe-O system are quite scattered, but when analyzing these data, it can be concluded that the oxygen concentration at which the temperature gradient of the surface tension reverses from negative to positive lies somewhere between
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0.002 and 0.005 wt. % O. This means that in the base material used in the present experiments already enough oxygen is present to cause a positive temperature gradient of the surface tension. As a consequence, it should be expected that the observed raise in oxygen content will not lead to a reversal in the flow profile, but to a stronger downward directed fluid flow and, hence, to improved penetration.

Earlier research carried out in the Welding Group of Delft University of Technology shows that the surface tension of the liquid metal in the weld pool can be determined by measuring the oscillation frequency of the weld pool [4.13] (see Appendix C). Use was made of this method to measure the surface tension of weld pools with and without SiO$_2$. Bead-on-plate experiments were carried out under travelling conditions using a standard GTA welding set-up. As described elsewhere [4.14], the weld pool is brought into oscillation by a pulsed current, after which the oscillation frequency can be calculated by analyzing the voltage data. To be able to determine the surface tension as a function of temperature, the experiments were carried out at different welding currents. The mean temperature of the weld pool was measured with a pyrometer immediately after extinguishing the arc, whereas the weld pool width was determined by measuring the weld bead width after welding.

In Fig. 4.9 the results of the surface tension measurements are depicted. It appears that in the case of welding without SiO$_2$ the surface tension lies around 0.8 N/m, while when welding with SiO$_2$ the surface tension appears to be about 0.1 N/m. The decrease in surface tension can be partly explained by the fact that the oxygen content in the latter case is higher. An additional factor that could play a role is the liquid SiO$_2$ floating on top of the weld pool, which would result in a smaller effective weld pool diameter. As a consequence a smaller surface tension is obtained.

It can also be seen in the figure that both in the case of welding without and with SiO$_2$ the surface tension only slightly increases with temperature. This last observation implies that Marangoni flow will not play an important role both in the case of welding without SiO$_2$ and in the case of welding with SiO$_2$.
The surface tension as a function of temperature for welds obtained without (o) and with SiO₂ (●).

**Electromagnetic forces**

Due to the divergence of the electric current in the weld pool, electromagnetic forces (Lorentz forces) will act on the molten metal in the weld pool. As stated before, these Lorentz forces are dependent on the current density \( j \) and the self-induced magnetic field \( B \) according to the equation:

\[
\vec{F}_L = \vec{j} \times \vec{B}
\]  

(4-3)

Under the assumption that the current flow is divergent (which is normally the case), the electromagnetic forces will cause a flow in the weld pool that is inward directed, resulting in a deep and shallow weld pool. Since this flow is proportional to the current density, an increased arc current will result in enhanced penetration, while a longer arc length will cause decreased penetration.
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When welding with SiO₂ as additive, molten SiO₂ is floating on top of the weld pool resulting in a smaller contact area between the arc and the workpiece. As a consequence, the current density and hence the Lorentz force acting on the weld pool will increase: the flow in the liquid metal will become stronger, which will promote weld penetration.

In the foregoing, two different phenomena were discussed that influence the weld pool formation when welding with SiO₂. First of all, the constriction of the contact area between arc and weld pool appears to play an important role. However, the maximum D/W ratio obtained by a point like heat source is 0.5 under the assumption that the heat flow in the workpiece is 3-D. Since the D/W ratio of welds obtained with SiO₂ exceeds this value, it must be concluded that arc root constriction is not the only mechanism involved. This indicates that the flow in the molten weld metal also contributes to the increased penetration. More specifically, it appears that Marangoni flow only plays a minor role, while enhanced penetration due to Lorentz forces is a significant effect, which co-operates with the effect of anode root constriction due to the presence of SiO₂.

4.4 Melting efficiency

It is evident that the use of SiO₂ as additive will also affect the melting efficiency of the welding process. The melting efficiency of the GTA welding process can be approximated by the equation [4.15]:

$$\eta_m = \frac{qAV}{VI}$$  \hspace{1cm} (4-4)

in which q represents the heat required to heat a given volume of material from room temperature to melting temperature and subsequently melt this volume, A the surface area of the transverse cross-section of the weld, v the travel speed, V the arc voltage and I the welding current.

By measuring the surface area of the weld cross-sections and taking the appropriate values for the remaining parameters, \( \eta_m \) was calculated for welds obtained without and with SiO₂.
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The results are presented in Fig. 4.10 in the form of plots of the cross-sectional area and the melting efficiency $\eta_m$ versus welding current, travel speed and arc length, respectively. The melting efficiency is determined by two factors. The first factor is the fraction of the heat that is transferred from the welding arc to the workpiece. The larger this fraction, the larger the melting efficiency. Generally speaking, the transferred heat increases with welding current, is independent of travel speed and decreases with arc length. The second factor that plays a role is the fraction of the heat transferred to the workpiece that is directly used for melting. This fraction increases with increasing temperature gradient in the weld pool and has an increased D/W-ratio as result.

It can be seen in Fig. 4.10a that increasing the welding current results in an increase of both the cross-sectional area and the melting efficiency. The increase of the melting efficiency can be ascribed to an increase of the fraction of the heat that is transferred from the arc to the workpiece. It appears that the addition of SiO$_2$ does scarcely affect the melting efficiency.

When increasing the travel speed, the cross-sectional area of the weld decreases due to the lower heat input caused by the increase in travel speed (see Fig. 4.10b). A slight increase of $\eta_m$ can be observed in the case of welding blank plates, which is due to the fact that relatively more heat is directly used for melting because of the larger temperature gradient in and around the weld pool. By the addition of SiO$_2$, this effect is enhanced due to contraction of the anode root.

As shown in Fig. 4.10c, increasing the arc length leads to a decrease in cross-sectional area in the case of welding without SiO$_2$, due to both a decrease of the heat transferred to the workpiece and a smaller temperature gradient in the weld pool. In the case of welding with SiO$_2$, a slight increase of the cross-sectional area can be observed. Apparently, the decrease in the heat input due to an increase in arc length is overshadowed by the more efficient use of the heat caused by the anode root constriction. The melting efficiency follows the same trend.

At this point it should be noted that in the definition of the melting efficiency overheating of the weld pool (heating to a temperature above the melting temperature) is not taken into account. Since in reality overheating will take place to a level which depends on the welding parameters, this will limit the reliability of the results.
Fig. 4.10  Cross-sectional area and melting efficiency as a function of welding current (a), travel speed (b) and arc length (c) for welds obtained without (o) and with SiO₂ (●).
4.5 Microstructure

In the foregoing it was shown that the use of SiO₂ as additive during welding leads to a considerable change in the heat input. Simultaneously, the chemical composition of welds obtained with SiO₂ was found to become different from that obtained without SiO₂. Both the heat input during welding and the chemical composition have a significant influence on the resulting microstructure of the weld.

During welding, the welding heat transferred to the workpiece is used for heating and melting, which will lead to the formation of a weld pool. Due to the heat conductivity of the material, the zone next to the weld pool will also be exposed to the welding heat. This results in the formation of the so-called heat affected zone (HAZ). Depending on the thermal cycle (heat input, peak temperature and cooling rate), different sub-zones can be distinguished in the weld and the HAZ. This is schematically depicted for mild steel in Fig. 4.11, whereas in Fig. 4.12 the different microstructures characteristic for the different sub-zones are shown.

The metal that melted and subsequently solidified during the welding cycle is referred to as weld metal. The microstructure of the weld metal is comparable with the structure that is formed during continuous casting. Depending on the cooling rate, different microstructures can be found in the weld metal. In the case of a fast cooling rate, it is possible that martensite is formed. With a moderate cooling rate different structures will be formed, the most important being grain boundary ferrite and acicular ferrite, while Widmannstätten ferrite can also be present in small amounts. At very low cooling rates, polygonal ferrite and pearlite will be formed as well. During arc welding under normal conditions (without pre-heating and post-quenching), the cooling rate is moderate.

In the heat affected zone different sub-zones can be distinguished, depending on the heat input and the distance from the fusion boundary:
Fig. 4.11 Schematic representation of the different microstructural sub-zones as a function of peak temperature in weld metal and HAZ of a mild steel weld.

Weld: a) weld metal; b) partially melted zone.
HAZ: 1) coarse-grained zone; 2) fine-grained zone; 3) partially transformed zone; 4) tempered zone.

coarse-grained zone \((1100 \, ^\circ C < T_p < T_m)\)

In the sub-zone close to the fusion boundary austenitic grain growth will take place, as the peak temperature will be between 1100 \(^\circ\)C and the melting point. Depending on the cooling rate, the resulting structure will be ferrite-pearlite (moderate cooling rate) or pearlite-ferrite-martensite (fast cooling rate).
Fig. 4.12 Microstructure of a weld in Fe360 in which the different sub-zones can be identified.
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**fine-grained zone (A_{c3}<T_p<1100 °C)**

As is the case in the coarse-grained zone, in the fine-grained zone the material will be completely converted to austenite. Because of the lower temperature, no grain growth will take place. As a consequence, the small austenite grains will be transformed to a fine-grained ferrite/pearlite structure.

**partially transformed zone (A_{c1}<T_p<A_{c3})**

In the sub-zone where the peak temperature lies between the A_{c1} and the A_{c3} lines in the iron-carbon phase diagram, partial transformation takes place. Especially pearlite will be converted to austenite and depending on the cooling rate pearlite, bainite or martensite will develop.

**tempered zone (T_p<A_{c1})**

In this sub-zone no phase transformation takes place due to the fact that the peak temperature remains below the A_{c1} line in the iron-carbon diagram. Nevertheless, some microstructural changes, such as spheroidization of pearlite and aging can be expected to occur.

Before taking the different sub-zones of the welds obtained in the present work into consideration, it is worthwhile to regard the HAZ as a whole. As stated before, welding with SiO₂ results in a higher heat input in the workpiece due to the higher arc voltage. Under the assumption that the process efficiency is the same for welding with and without SiO₂, it can be calculated that the heat input is about 10-15 % higher in the case of welding with SiO₂. As can be derived from Rosenthal’s equations (see section 4.3.1), the width of the HAZ increases linearly with the heat input both in the case of a 2-D heat flow and in the case of a 3-D heat flow. When measuring the width of the HAZ of welds obtained without and with SiO₂ (see Fig. 4.2), it appears that the width of the HAZ in the case of welding with SiO₂ is indeed about 10-15% larger.

In addition to a larger HAZ, a higher heat input will also lead to a smaller cooling rate and, hence, to changes in the microstructure of weld metal and heat affected zone. To find out to what extent these weld regions are affected by the addition of SiO₂ during welding, the microstructure of welds obtained without and with SiO₂ was studied in more detail.
Fig. 4.13  Microstructure of weld metal of welds obtained without (a) and with (b) SiO$_2$. 
Fig. 4.14  Microstructure of the fine-grained zone of welds obtained without (a) and with (b) SiO₂.
Chapter 4

In Fig. 4.13 the microstructure of weld metal of welds obtained without and with SiO₂ are shown. It can be seen in this figure that in the case of welding with SiO₂, more grain boundary ferrite and less acicular ferrite is present than in the case of welding without SiO₂. As is predicted by the CCT-diagrams for mild steel, this change in microstructure is caused by a slower cooling rate [4.16], which is expected when welding with SiO₂.

In Fig. 4.14 the microstructure of the fine-grained sub-zone of welds obtained without and with SiO₂ are shown. It appears that in the case of welding with SiO₂, the resulting structure is coarser than in the case of welding without SiO₂. Again this effect is caused by the slower cooling rate in the case of welding with SiO₂.

To determine to what extent the difference in microstructure affects the mechanical properties of the welds, Vickers hardness tests and tensile tests were carried out. The results are described in the next section.

![Graph](image)

Fig. 4.15 Vickers hardness as a function of relative depth of welds obtained by welding without (o) and with (●) SiO₂.
The influence of additives on the weld pool

Fig. 4.16 Stress-strain curves for base material and welds obtained without and with SiO₂.
4.6 Mechanical properties

To examine the effect of SiO₂ as additive during welding on the mechanical properties of the weld, the hardness of welds obtained without and with SiO₂ was determined by means of Vickers hardness measurements, performed on transverse cross-sections of the welds. The results are depicted in Fig. 4.15. In this figure the Vickers hardness of the welds is plotted as a function of the relative depth, the vertical distance from the top surface expressed in fractions of the total weld depth. In this way, the boundary between weld metal and HAZ is situated at relative depth 1.00 for both welds. It can be seen that the hardness of the weld metal is higher than the hardness of the base material and that the use of SiO₂ leads to a lower hardness of the weld metal. This can be explained by the fact that the cooling rate is slower in the case of welding with SiO₂, as concluded in the previous section, which causes a reduced hardness [4.16]. In the same way it can be argued that, due to the coarser grain structure of the HAZ, the hardness of the HAZ is lower in the case of welding with SiO₂.

In addition to hardness measurements, also tensile tests were performed. Welding experiments were carried out on mild steel plates of 2 mm thickness, resulting in fully penetrated welds both in the case of welding without SiO₂ and in the case of welding with SiO₂. Standard tensile specimens (dp₁₀) were machined with their length direction normal to the weld. The specimens were tested at a rate of 4 mm/min on an Instron testing machine (50 kN). Typical examples of the strain-stress curves obtained are depicted in Fig. 4.16.

It was found that all specimens fracture in the base material. The ultimate tensile strength (σₚ), lower yield point (σₚₚ) and strain to fracture (εₚ) were determined in five-fold. The mean values are depicted in Fig. 4.17 and Fig. 4.18.

It appears that for the base material and the different welds, the values of the ultimate tensile strength and lower yield point lie in the same range, which is not surprising given the fact that all specimens break outside the weld region. Thus, it can be concluded that welding with additives is not detrimental for the mechanical strength of the weld. However, a larger difference is found in the values for the strain to fracture. All welds appear to display smaller strain to fracture values than the values obtained in the case of the base material. This can be explained as follows. When examining the specimens after fracture, it can be observed that less strain has occurred in the region of the weld, as schematically shown in Fig. 4.19, due to the fact that the weld metal is harder than the surrounding base.
metal. Hence, a correction should be made which can account for the fact that the length of
the reduced section in the case of the welded specimens is shorter. The observation that the
values for strain to fracture of welds obtained with SiO\textsubscript{2} is higher than those observed for
welds without SiO\textsubscript{2} is consistent with the finding that the hardness of the weld metal of
welds obtained with SiO\textsubscript{2} is lower than the hardness of welds obtained without SiO\textsubscript{2}. As a
consequence, the correction for the shorter reduced section should be smaller.

![Graph showing tensile strength and yield point](image)

Fig. 4.17 Ultimate tensile strength, $\sigma_u$, and lower yield point, $\sigma_y$, of base material and
welds obtained without and with SiO\textsubscript{2}.

![Graph showing strain to fracture](image)

Fig. 4.18 Strain to fracture ($\varepsilon_f$) of base material and welds obtained without and with
SiO\textsubscript{2}.
Fig. 4.19  Schematic drawing (top view) of a welded specimen after fracture. In the region marked by the arrows no strain occurs.

4.7  Conclusions

This chapter concerns the influence of additives on the weld pool, with emphasis on the effect that SiO$_2$ has on the weld pool formation and on the properties of the weld. The following conclusions can be drawn:

- the use of additives, and especially oxides, improves weld penetration;
- welding with SiO$_2$ as additive results in a change in contact area between arc and weld pool as well as a change in the weld pool flow due to Lorentz forces;
- the melting efficiency of the welding process increases due to the presence of SiO$_2$;
- due to the higher heat input accompanying welding with SiO$_2$, the microstructure of the weld metal contains more grain boundary ferrite and less acicular ferrite, which results in a lower hardness of the weld metal;
- the HAZ of welds obtained with SiO$_2$ is broader due to the increased heat input; in addition, the microstructure is coarser which results in a decrease in Vickers hardness;
- no difference is observed between the ultimate tensile strength and the lower yield point of base material and welds obtained without and with SiO$_2$; however, the value of the strain to fracture of the welds is lower than that of the base material due to the fact that the weld metal region is harder and, hence, does not contribute to the strain.
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SENSORS AND CONTROL SYSTEMS IN ARC WELDING

In Chapter 3 it was suggested that the effect that certain additives (in particular SiO₂) have on arc voltage could be used as a tool for seam tracking during welding. The feasibility of this approach will be addressed in chapter 6. In the present chapter the existing sensors and control systems used in arc welding are reviewed.

The last decade has seen a growing interest in arc welding automation and robotizing [5.1-5.4]. Sensors, controllers, control software, robots and automatic welding machines are continuously being invented and developed. The raised interest in the topic is related to the advantages that automation and robotizing offer, like productivity increase and quality improvement. However, a sensor or control system that satisfies all purposes has not been developed until now; for each specific purpose or application, a suitable sensor or robot has to be selected.

Sensors can be used to detect the following disturbances or deviations:
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- work shape errors;
- setting errors;
- variation in groove shape;
- tack beads;
- welding heat distortion;
- jig errors.

Unfortunately, the welding process often hampers the correct action of many sensor systems. The phenomena that can give rise to problems are for example arc light, arc heat, spatter, electromagnetic induction, bending and deflection of the electrode wire, fluctuation in the wire feeding speed, wear of contact tips and changes in welding conditions and arc shape.

In practice it is impossible to exclude all these disturbances directly. Therefore, most sensors must be equipped with additional functions to eliminate them.

In general, sensors must be:
- capable to handle the welding process adequately precise;
- free from welding process-induced disturbances (heat, light, spatter, etc);
- sufficiently durable;
- small and light;
- highly reliable;
- inexpensive;
- easy to maintain;
- applicable in a wide range of conditions.

Sensors are being applied in welding control systems, which can be distinguished as follows on the basis of application:
- position sensing and seam tracking;
- adaptive control of welding conditions;
- weld monitoring and quality control.

Roughly speaking, sensors can be divided into two main groups, viz. tactile sensors and contactless sensors. Especially the latter group is becoming increasingly important. In the
mean time, the sensors in this group become more and more sophisticated and also more complicated. The most important sensors that are used at present will be discussed in the next sections.

5.1 Tactile sensors

In general tactile sensors can serve three different purposes [5.5]:

- positioning of the welding torch;
- detection of the weld seam;
- protection against collisions.

5.1.1 Electrode contact sensor [5.6]

The electrode contact sensor (Fig. 5.1) detects the change in electric potential when a welding wire or probe makes contact with the base material. The actual position of the probe for each contact point is stored. The so-called 'Touch system' yields the precise 3-d position of the base material by the combination of these points. Another system that uses touch sensing is called 'Automatic Torch Definition' and is meant to locate the welding wire tip. The function of this sensor is to find the weld seam and to place the torch in the right position. Because the sensing takes place before the actual welding procedure, this kind of sensors can be applied in different welding processes. A disadvantage of these sensors is that they are not reliable in case of strongly oxidized surfaces.

Fig. 5.1 Electrode contact sensor.
5.1.2 Mechanical sensors [5.3]

Mechanical contact sensor (Fig. 5.2a)
The mechanical contact sensor is applied in essentially the same way as the electrode contact sensor. However, in this case a mechanical switch (e.g. a micro-switch) detects the contact instead of a change in electric potential. The welding torch moves slowly towards the surface of the workpiece. If contact is made, the micro-switch stops the search movement and the coordinates of the torch are stored as reference point. The combination of a number of points results in knowledge of the 3-D position of the base material. In this way, the sensor can be applied to find the weld seam.

Mechanical contact probe (Fig. 5.2b)
In case of the mechanical contact probe, a probe in front of the torch scans the weld seam. In general, the position of the torch is controlled in two directions perpendicular to the welding direction. Which kind of probe is chosen, depends on the weld seam.
It is obvious that this sensor cannot be applied in each situation due to lack of space.

![Diagram of mechanical sensors](image)

Fig. 5.2 Mechanical sensors: a) contact sensor; b) contact probe.
5.2 Contactless sensors

5.2.1 Arc phenomena sensors

Arc sensor with torch height control [5.3]
Two sensors should be mentioned under this heading, namely the AVC (automatic voltage control) sensor and the ACC (automatic current control) sensor. These sensors make use of the fact that arc voltage and welding current depend on the distance between torch and workpiece. When the torch height increases, the arc length increases as well. This results in an increase in arc voltage (in the case of constant current) or a decrease in current (when working with a constant voltage). By monitoring the voltage or current, real time correction of the torch height can be realized.

Arc sensor with oscillating torch [5.7, 5.8]
The arc sensor with oscillating torch (Fig. 5.3) is developed for seam tracking. The principle is essentially the same as that of the arc sensor for torch height control. The torch is oscillated periodically over the groove and the welding current is measured continuously. The principle of this seam tracking sensor is based on the fact that the welding current (in the case of a constant voltage power source and a constant wire feeding speed) is equal on both sides ($I_{\text{left}} - I_{\text{right}} = 0$), as long as the torch is situated symmetrically over the groove. Because the sensor needs the welding process for its function, it is not suitable to detect the start of the seam. This implies that an additional sensor (like for instance a tactile sensor) is needed for seam finding in combination with seam tracking. Another restriction of this sensor is that the method can only be applied in case of seams with a distinct groove shape.
\[ \Delta L \sim \Delta s \]

Fig. 5.3   Arc sensor with oscillating torch.

Fig. 5.4   Arc sensor with magnetic arc deflection.

Fig. 5.5   Arc sensor with two wires.

Fig. 5.6   Arc sensor with high-speed rotating arc.
Sensors and control systems in arc welding

Arc sensor with magnetic arc deflection [5.9]
The arc sensor with magnetic arc deflection (Fig. 5.4) is a variant of the arc sensor with oscillating torch. The torch is not oscillated as a whole, but only the arc is deflected alternately to both sides in a regular pattern. The arc deflection is realized by the application of an alternating magnetic field.

Arc sensor with two wires [5.7]
For submerged arc welding, seam tracking systems have been developed using the twin arc process (Fig. 5.5). The torch is placed in such a way that each arc is burning on one flank of the weld groove. Both arcs are fed by the same power source and both wires have the same wire feeding speed. Consequently, the resulting welding current through each wire depends only on the contact-tip-to-wire distance. Correct welding is achieved when the current through the left wire equals the current through the right wire.

Submerged welding is normally used to weld long straight seams in thick plate material. Because of the high deposition rate of the process, it is also interesting for welding curved seams in thick plates. With the twin wire sensing principle it becomes possible to guide the torch along curved seams via height and side control and with adaptation of the torch orientation.

Arc sensor with high-speed rotating arc [5.10]
The arc sensor with high-speed rotating arc (Fig. 5.6) is another variant of the arc sensor. Just as the normal arc sensor, this sensor is meant to control torch height and can be applied for seam tracking.

Different rotating mechanisms can be used as shown in Fig. 5.7. In the first type the electrode itself rotates axially. The current has to be supplied via a carbon brush with friction disk. In the second case the electrode swings around, while the top of it remains in one place. Consequently, the current can be supplied directly to the electrode. The advantage is that this type can be designed in a more compact size. The rotation of the electrode causes variations in the voltage or current. By monitoring the voltage or current it can be decided whether the average place of the electrode is situated in the middle of the groove.

The advantage of the high-speed rotating arc is that the oscillating speed is larger in comparison with the conventional oscillating torch (Fig. 5.3). This makes it possible to weld thinner plates and to increase the welding speed.
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Fig. 5.7 Two different arc rotation types: a) conventional method; b) improved method.

5.2.2 Optical sensors

Point sensor (Fig. 5.8a) [5.1]
The optical point sensor, which uses a photodiode or phototransistor, has been developed for seam tracking control. The sensor oscillates perpendicular to the weld seam and detects light reflected or emitted from the base material. The position of the sensor and the quantity of light received by the sensor are a measure for the position of the torch with respect to the weld seam.

Linear sensor (Fig. 5.8b) [5.11]
The linear optical sensor is based on the simplest form of triangulation. A point light source (like for instance an infrared light beam) irradiates the base material. The reflected light is caught by an optical device and projected on a linear sensor (ccd). The control system employs the principle that a light-receiving position changes by \( \Delta h \) when its distance from the base material changes by \( \Delta H \). An abrupt change in the signal indicates the weld seam. In this way the sensor can be used to measure the torch height and to detect the weld seam.
Sensors and control systems in arc welding

Fig. 5.8 Four different optical sensors: a) point sensor; b) linear sensor; c) image sensor (I); d) image sensor (II).
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Image sensor (I) (Fig. 5.8c) [5.1]
In the case of the optical image sensor the weld seam is irradiated by a slit light source. The light creates a light-line across the weld seam. A camera detects the image, which represents the profile of the weld seam. After processing the image, the place and form of the weld seam can be determined.

Image sensors become increasingly multifunctional. An example is the Integrated Optical Sensor (IOS) [5.12]. The IOS is a multifunction feedback control sensor that continuously monitors three distinct process features:

- weld pool position and width (to control the position of the weld pool in relation to the joint);
- sensor-to-workpiece distance;
- weld bead centerline cooling rate (to control the final metallurgical state of the weld bead and heat-affected zone).

Image sensor (II) (Fig. 5.8d) [5.1]
This sensor is aimed at optical weld bead control. A camera directly films the weld bead and surroundings, which yields direct information about the temperature distribution in and around the weld pool. A process unit analyses the images. In this way control of the weld pool width and prevention of weld defects can be achieved.

Infrared sensor [5.13]
Recently, a new seam tracking system with scanning infrared sensor was developed. A point infrared sensor mechanically scans the groove to obtain information of the whole groove area. The sensor is capable to realize automatic seam tracking in both horizontal and vertical direction. The groove pattern, the position of the weld seam and the condition of the seam tracking process can be displayed in real-time on an oscilloscope.

The infrared sensor can also be used for joint penetration control. In this case the controller utilizes infrared radiation emission, usually monitored from the underside of the weld.
**Concentration sensor** (Fig. 5.9) [5.14]

Recent research has shown that convection of the liquid weld metal can provide an interesting tool for establishing predetermined root penetration control. A Mg-Ni alloy tracer is attached to the root side of the workpiece. In the case of root penetration, the alloy is picked up by the weld metal and carried upwards to the surface by convection. After evaporation the tracer can be detected in the arc by spectroscopic analysis of the Mg 518 nm line. The intensity of the Mg emission depends on the penetration width.
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Of course other elements or alloys could be considered as tracer material. Requirements for suitable tracer elements are:

- sufficient emission output of characteristic wavelengths not interfering with other wavelengths of the arc spectrum;
- good applicability to the plate material;
- minimum loss of tracer material due to fusion;
- sufficient solubility at melting temperature of plate material;
- high partial vapor pressure at pool surface temperature;
- no detrimental influence on weld metal convection;
- compatibility to weld metal properties of residual tracer contents.

5.2.3 Weld pool oscillation sensor [5.15]

The weld pool oscillation sensor is meant to control weld pool penetration. The principle of this sensor is based on the following (Fig. 5.10). After triggering the weld pool by means of an arc current pulse, the weld pool starts to oscillate. The natural oscillating frequency can be determined optically or by measuring the arc voltage variation. It appears that a partially penetrated weld pool oscillates in a different mode (mode 1) and with a different frequency compared to a fully penetrated weld pool (mode 3). Furthermore, a relationship exists between the natural frequency of oscillation and the diameter of the weld pool. Hence, it is possible to sense and control the weld pool width and the weld pool penetration by monitoring the weld pool oscillation frequency during welding.

5.2.4 Ultrasonic sensor (Fig. 5.11)

Ultrasonic sensing is another way to control penetration during welding [5.16]. In this approach an ultrasonic sensor is moved over the workpiece. The ultrasonic beams are reflected at the different phase transitions and detected by the sensor. Differences in beam path length give information about the geometry of the weld pool and about the weld pool penetration. Fenn [5.16] claims that the ultrasonic sensor can be used for three different purposes at the same time (Fig. 5.12):

- ultrasonic measurement and control of the weld pool depth;
• joint tracking (via use of two ultrasonic probes);
• acquisition of weld quality information.
Recently such an ultrasonic control device for robotic welding has being developed that controls the three variables mentioned above [5.17].

Fig. 5.11 Ultrasonic sensor.

Fig. 5.12 A multi-purpose ultrasonic sensor. Signal A is used for penetration control, signal B for joint tracking and signal C for quality control: left) top view; right) front view.
5.2.5 Acoustic sensor

In principle the acoustic signals generated by the welding arc are a source of information about the welding process, which can be used for feedback by manual welders. The arc shape and size (directly related to the electrical input) determine the sound of the arc, which means that the sound of the arc informs the operator about the size and shape of the arc [5.18]. Based on this principle Kaskinen and Mueller [5.19] developed an acoustic sensor for arc length control in GTA welding. They showed that the frequency of the acoustic signal generated by the arc is proportional to the arc length. Hence, arc sound can be processed to provide a feedback signal for arc length control.

Another way to use the acoustic properties of the arc was reported by Johnson et al. [5.20]. It appears that it is possible to distinguish between different metal-transfer modes during welding by monitoring the arc sound.

5.3 Conclusions

In the foregoing a large number of welding sensors was reviewed. It appears that most sensors can be applied in specific situations and for specific applications only. Based on the present knowledge and expertise the following conclusions can be drawn:

- contact sensors are robust, but their use is limited in case of contaminated surfaces or in situations with insufficient workspace;
- through-the-arc sensors are easy to implement but, in case of seam tracking, only applicable for groove shaped welds;
- image sensors are sophisticated, but expensive; these sensors also require a lot of space and can readily be disturbed by the welding process;
- the weld pool oscillation sensor, which is easy to implement in the welding process, is a promising tool for penetration sensing.

Summarizing, it can be stated that the search for robust, cheap and multifunctional sensor and control systems is still of great importance for the welding industry.
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APPLICATION OF ADDITIVES IN GTA WELDING

As can be concluded from Chapter 5, sensing and control in arc welding has become increasingly important. However, the development in this area is still in its initial state and the quest for a robust, simple and multifunctional sensor system is therefore still continuing. In addition, research is still carried out to improve the existing welding processes like GTA welding.

In Chapter 3 and Chapter 4, the influence of additives on the welding arc and the weld pool was discussed extensively. It was found that the preselected additives, in particular $\text{SiO}_2$, influence various properties of the arc and the weld pool, especially arc voltage and weld pool penetration. At this point the question arises whether the effects that additives have on the arc welding process can be used in specific applications. Until now, only use has been made of the effect of additives on penetration. In fact, additives are being applied in the form of fluxes to achieve enhanced penetration in a variant of regular GTA welding: Activated Tungsten Inert Gas (ATIG) Welding [6.1, 6.2]. The fluxes used to achieve this improvement usually consist of different components, which sometimes are hazardous in
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terms of environment and health (e.g. chromium oxides or different fluorides). In addition, these fluxes are not yet commercially available.

As stated earlier, the effect of additives on the arc voltage can also be used for position sensing (seam tracking) during welding. The basic idea of this approach is to mark the seam prior to welding with a suitable additive that exerts a detectable effect on arc voltage. By continuously measuring the arc voltage during the welding process, it should be possible to determine in real time whether the torch is in the right position with respect to the weld seam.

In this chapter two practical applications of additives in GTA welding will be considered: improvement of weld penetration and real time position sensing with feedback control.

6.1 Improvement of weld penetration

One of the most important features of a weld is its geometry and, in particular, its penetration or depth-to-width (D/W) ratio. Ideally, a weld has a high D/W ratio: the higher this ratio, the more effective the welding process and the smaller the possibility of cast-to-cast variations [6.3].

To explore the possibilities of applying SiO₂ as flux to improve weld penetration and to reduce the possibility of cast-to-cast-variations, bead-on-plate experiments were carried out on mild steel and two different casts of stainless steel without and with SiO₂. Both partial weld penetration and full weld penetration were considered.

6.1.1 Partially penetrated welds

The measurements of the D/W ratio carried out thus far (Chapter 4) concerned welds in mild steel only. However, when considering the possibility of applying SiO₂ for penetration improvement, it is worthwhile to take stainless steel into account as well. Due to the presence of surface-active elements, these steels are susceptible to cast-to-cast variations, which can give rise to serious problems. Welding with SiO₂, however, is expected to result in a reduction of these variations due to an improved D/W ratio, caused by an increased heat input and a reduced arc-workpiece contact area.
To determine whether SiO$_2$ can be used for penetration improvement in the case of GTA welding of different types of steel and to find out to what extent the chemical composition of the base material plays a role, bead-on-plate experiments were carried out. As base material, plates of mild steel Fe 360 (250x200x10 mm) and two different heats of austenitic stainless steel AISI304 (250x200x10 mm, 250x100x8 mm) were used. The chemical compositions of the steels are listed in Table 6.1.

Fig. 6.1 Welds obtained without (a) and with (b) SiO$_2$ in AISI304HS (I= 250A).
Table 6.1  Chemical composition of Fe 360 and AISI 304 (LS/HS*).

<table>
<thead>
<tr>
<th></th>
<th>Mn</th>
<th>Cu</th>
<th>Si</th>
<th>C</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>P</th>
<th>O</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe 360</td>
<td>0.74</td>
<td>0.22</td>
<td>0.32</td>
<td>0.067</td>
<td>0.141</td>
<td>0.018</td>
<td>0.101</td>
<td>0.029</td>
<td>0.011</td>
<td>0.031</td>
</tr>
<tr>
<td>AISI 304 LS</td>
<td>1.35</td>
<td>ca.0.42</td>
<td>0.37</td>
<td>0.024</td>
<td>17.8</td>
<td>0.28</td>
<td>8.37</td>
<td>0.03</td>
<td>0.017</td>
<td>≤0.005</td>
</tr>
<tr>
<td>AISI 304 HS</td>
<td>1.45</td>
<td>ca.0.49</td>
<td>0.29</td>
<td>0.046</td>
<td>17.6</td>
<td>0.54</td>
<td>8.65</td>
<td>0.04</td>
<td>0.021</td>
<td>0.015</td>
</tr>
</tbody>
</table>

*) LS = low sulfur; HS = high sulfur

Welding experiments were carried out without and with SiO₂ as additive under standard conditions as listed in Table 3.2, except for the current which was chosen to be 140 A and 250 A. Of each weld a transverse cross-section was made, which was used for microscopic examination. Also the depth, width, surface area and D/W ratio of the weld cross-section were determined. In Fig. 6.1 typical examples of welds in stainless steel AISI 304HS obtained without and with SiO₂ are shown. The D/W ratio of welds obtained without and with SiO₂ in the different types of steel at 140 A and 250 A are depicted in Fig. 6.2.

It can be seen that in all cases the use of SiO₂ as additive results in a large improvement in weld penetration. Due to the fact that the heat conductivity of mild steel is larger than that of stainless steel, the effect on the weld penetration is largest in the latter case. Another important observation is that in case of welding stainless steel, the variation in weld penetration due to the difference in the chemical composition disappears when welding with SiO₂. This observation in combination with the fact that the increase in penetration is much higher than that reported in other work [6.4, 6.5], supports the conclusion reached in Chapter 4 that Lorentz flow rather than Marangoni flow plays the decisive role.

This is confirmed by the fact that the increase in penetration becomes larger at higher currents for both mild steel and stainless steel.
Fig. 6.2 Depth-to-width ratio of welds obtained without and with SiO₂ in different types of steel at 140 A and 250 A.

6.1.2 Fully penetrated welds

As mentioned above, an important advantage of welding with SiO₂ is the reduction of differences in penetration due to cast-to-cast variations. Another beneficial effect of using SiO₂ is that, due to the increased penetration, fully penetrated welds can be obtained by welding with smaller heat input. To illustrate this effect, additional welding experiments were carried out using 3 mm thick plates of Fe360 and AISI304 without and with SiO₂. An example of the results obtained is presented in Fig. 6.3. This example shows that in the case of welding stainless steel AISI304 fully penetrated welds can be achieved by applying a current of 110 A, while in the presence of SiO₂ only 80 A is needed. Furthermore, it appears that Fe360 and AISI304 plates of 5 mm thickness can be easily welded in a single
pass with only 150 A and 140 A, respectively. Without SiO$_2$ addition, it is hardly possible to achieve good full penetration welds in plates of this thickness: under these conditions the weld bead becomes too broad and sagging occurs.

Fig. 6.3 Fully penetrated welds in AISI304: a) without SiO$_2$ at 110 A; b) with SiO$_2$ at 80 A.
Fig. 6.4 Two different approaches of sensing by means of additives: up-hill (region I) and down-hill (region II)

6.2 Position sensing

6.2.1 Three variants of sensing with additives

As stated above, it should be expected that the effect of additives on arc voltage can be used for position sensing during GTA welding. In Fig. 6.4 a typical example of the influence of SiO₂ on arc voltage is presented. The figure clearly shows that two essentially different approaches can be followed for a sensing system based on additive influences: up-hill sensing and down-hill sensing. The first approach makes use of the increase in arc voltage when the arc runs into a region covered with additive (region I). When this voltage increase exceeds a preset threshold value, a signal is produced which can be used to trigger path correction (change in travel direction). In practice, this can be realized in two different ways: the arc is forced to remain between two zones covered with additive (Fig. 6.5a) or the arc is forced back to one zone covered with additive (Fig. 6.5b). The second approach utilizes the decrease in arc voltage when the arc runs out of the additive covered zone (region II). In this case, the change in direction can be triggered by a preset decrease in arc voltage. This can be realized by marking the seam itself with the additive (Fig. 6.5c).
up-hill sensing (the arc is forced to remain between two additive covered zones)

up-hill sensing (the arc is forced to return to the additive covered zone)

down-hill sensing (the arc is forced to remain on the additive covered zone)

Fig. 6.5 Three different ways of applying an additive (SiO₂) for position sensing.
6.2.2 Preliminary experiments

To test the new sensing approach in a fast and simple way, preliminary experiments were carried out using the GTA welding set-up described in previous chapters. Because the up-slope in the voltage-distance diagram is steeper than the down-slope, it was decided to focus on the feasibility of the up-hill sensing approach. In the testing experiments the welding torch (arc) travels at fixed travel speed (positive or negative) between two zones covered by SiO₂, as schematically shown in Fig. 6.6.

![Schematic diagram showing additive-assisted position sensing.](image)

Fig. 6.6 Preliminary testing of additive-assisted position sensing.

In Fig. 6.7 the results of an experiment carried out under standard welding conditions (I = 180 A, l = 3 mm, v = 2 mm/s) are shown. In this case the threshold voltage was set at 0.3 V. The figure shows that when the arc enters one of the two SiO₂ covered zones, the arc voltage increases. As soon as the arc voltage exceeds the threshold value (0.3 V) the travel direction is reversed. In this way the torch is forced to remain within the confined area between the two SiO₂ covered zones.

To further test the feasibility of additive assisted position sensing, it was decided to carry out additional experiments under more realistic welding conditions.
Fig. 6.7  Results of preliminary sensing experiments following the up-hill sensing approach.
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Fig. 6.8 Modified GTA welding set-up with two degrees of freedom in movement to approximate realistic welding conditions. (1 = stepper motor travel bench, 2 = travel bench, 3 = workpiece, 4 = torch, 5 = stepper motor torch).

6.2.3 Experimental set-up and measuring program

To be able to test the new sensing system under more realistic welding conditions, the GTA welding set-up was modified as shown in Fig. 6.8. In this modified set-up, the construction of the torch was changed from fixed to movable, resulting in a system of two degrees of freedom (forward movement and sideward movement).

To realize real time feedback control, the Labview program used in the previous phases of the study was extended and refined. The resulting user interface is shown in Fig. 6.9. Before starting the welding process, all required welding parameters are set to their desired value: start current (default low, to be able to ignite the arc with a carbon stick), welding
current, forward travel speed and direction, sideward travel speed and direction, weld length (to prevent the torch to run off the plate). The welding procedure is schematically shown in Fig. 6.10.

During welding, the arc voltage is monitored continuously. To keep the feedback system as flexible as possible, it is necessary to regularly compare the subsequent voltage data, instead of comparing the incoming data with a preset value. The principle of the feedback procedure is schematically shown in Fig. 6.11. The arc voltage, \( V_i \), is measured continuously at a certain sample rate. Subsequently, the actual voltage, \( V_{i-n} \), is compared with the voltage of \( x \) measurements earlier, \( V_{i-n-x} \).

As can be seen in Fig. 6.4, the arc voltage changes gradually instead of abruptly when the arc enters a SiO\(_2\) covered zone. It is evident that the feedback system has to account for this phenomenon. To achieve the optimum in the reaction time of the system, mutual tuning of sample frequency (voltage measurements), comparison frequency \( (n_i \text{ with } n_{i-x}) \) and threshold value is necessary.

![Typical example of the Labview user interface.](image)

Fig. 6.9  Typical example of the Labview user interface.
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Fig. 6.10  Schematic representation of the welding procedure.

Fig. 6.11  Schematic representation of the feedback procedure.
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To prevent the system from overreaction (after a reversal in sideward torch direction it will take some time before this is notable in arc voltage), the last step ‘no reaction on the next n occasions that ΔV>threshold’ is obligatory. The value of n depends on the sample rate. With the set-up and program described above, welding experiments were carried out under the conditions as listed in Table 6.2.

Table 6.2 Welding conditions.

<table>
<thead>
<tr>
<th>workpiece material</th>
<th>Fe 360 plate, 250x200x10 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrode material</td>
<td>tungsten, 2% thoria</td>
</tr>
<tr>
<td>electrode diameter</td>
<td>2.4 mm</td>
</tr>
<tr>
<td>electrode top angle</td>
<td>60°</td>
</tr>
<tr>
<td>polarity</td>
<td>electrode negative</td>
</tr>
<tr>
<td>welding current</td>
<td>180 A</td>
</tr>
<tr>
<td>arc length</td>
<td>3 mm</td>
</tr>
<tr>
<td>shielding gas</td>
<td>argon</td>
</tr>
<tr>
<td>shielding gas flow rate</td>
<td>5 l/min</td>
</tr>
<tr>
<td>travel speed</td>
<td>1.0 mm/s</td>
</tr>
<tr>
<td>torch speed</td>
<td>1.0 mm/s</td>
</tr>
</tbody>
</table>

The following initial values for the feedback system were chosen:

- sample rate 1/300 ms
- threshold voltage 0.3 V
- comparison rate compare \( V_{i=n} \) with \( V_{i=n-4} \)

After analysis of the results of the experiments, optimization of the feedback values was carried out.

6.2.4 Validation experiments

Up-hill sensing between two additive covered zones

With the equipment and welding conditions described above, welding experiments were carried out, using up-hill sensing between two additive covered zones. Two examples of
the results obtained are shown in the photographs of Fig. 6.12 and Fig. 6.13. In Fig. 6.12, the situation is shown in which the arc is forced to remain between the narrowing space between the two SiO₂ covered zones, whereas Fig. 6.13 shows the situation in which the arc is forced to follow a path prescribed by two SiO₂ covered zones. The figures clearly illustrate that adaptive control during GTA welding using up-hill sensing is possible. In Fig. 6.14 an example is given of a typical voltage versus distance plot obtained during up-hill sensing between two SiO₂ covered zones. Every voltage peak in Fig. 6.14a indicates a reversal in sideward torch direction.

In Fig. 6.14b, ΔV (Vᵣ - Vᵣ₋₄) is given as a function of distance (time). Also indicated in this figure is whether or not (true or false) ΔV exceeds the preset threshold value of 0.3 V. The number of ‘true’ reversals in sideward torch direction, which is given above the points, is larger than one in all cases. Consequently, it should be possible to refine the feedback system. Analysis of the available voltage data indicates that the feedback system should be able to function also with ΔV (Vᵣ₋₄ - Vᵣ₋₅₋₃) and a threshold value of 0.15 V. With the refined parameters, the experiments were repeated. On the basis of the results, which are presented in Fig. 6.15, it can be concluded that sensing with the refined parameters is indeed possible: when using the refined parameters, the average ΔV and the number of hits per occasion decrease, which results in a smaller reaction time and, hence, in faster and more accurate sensing.

**Up-hill sensing along one additive covered zone**

To be able to test up-hill sensing along one additive covered zone, a minor change in the feedback mechanism was made. After the last step of the procedure shown in Fig. 6.11 the following additional step was incorporated:

```
reverse sideward direction to original direction after m measurements
```

The size of m should be selected depending on both torch speed and sample frequency.

Experiments were carried out using the parameters listed above. As an example of the results obtained, a photograph of the resulting weld is shown in Fig. 6.16. It appears that up-hill sensing along one additive covered zone can be considered as a real alternative for up-hill sensing between two additive covered zones. However, some problems might occur with the feedback system described above when the weld seam to be followed is sharply
curved. Under these conditions the arc will not be able to leave the additive covered zone anymore when the last step is too short. As a result of this, the arc voltage will remain high and the system will cease to react properly. This problem can be solved by incorporating a demand for voltage decrease in the last step of the feedback procedure.

Fig. 6.12  Adaptive control using up-hill sensing between two additive lines: the arc is forced to remain between the narrowing space between two SiO\textsubscript{2} covered zones.
Fig. 6.13 Adaptive control using up-hill sensing between two additive lines: the arc is forced to follow a path prescribed by two SiO$_2$ covered zones.
Fig. 6.14  Results of the validation experiments for up-hill sensing between two additive covered zones.

a) Voltage versus distance (time);

b) $\Delta V (V_{i,n} - V_{i,n-4})$ versus distance (time) and the number of ‘trues’ per torch direction reversal.
Fig. 6.15  Results of the experiments carried out with the refined parameters.
a) Voltage versus distance (time);
b) $\Delta V (V_{i-n} - V_{i-n-3})$ versus distance (time) and the number of ‘trues’ per torch direction reversal.
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Fig. 6.16  A typical example of up-hill sensing along one additive covered zone.

**Down-hill sensing**

To test the feasibility of down-hill sensing, experiments were carried out in which in the feedback procedure (see Fig. 6.11) the discrimination step was altered to:

\[ \Delta V < \text{threshold?} \]
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During the experiments it appeared that the parameters of the feedback system were too sensitive for the larger fluctuations in the arc voltage when welding on SiO₂. As a consequence of this, overreaction of the system occurred. Taking a larger threshold value could solve this problem, but a larger threshold value leads immediately to an increase in reaction time.

6.2.5 Possibilities and limitations of additive-assisted position sensing during GTA welding

On the basis of the results presented in the foregoing, it can be concluded that of the different approaches of additive-assisted position sensing up-hill sensing, and in particular up-hill sensing between two additive covered zones, is the most promising.

To further explore the application range of the up-hill sensing system, a series of experiments was carried out using the welding parameters listed in Table 6.3.

Table 6.3 Welding parameters to test the applicability of the new sensing system.

<table>
<thead>
<tr>
<th>welding current (A)</th>
<th>arc length (mm)</th>
<th>traverse speed (mm/s)</th>
<th>torch speed (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 75</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.2 125</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.3 180</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.4 250</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.5 300</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2.1 180</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2.2 180</td>
<td>6</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3.1 180</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3.2 180</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3.3 180</td>
<td>3</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>4.1 180</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>4.2 180</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>4.3 180</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>
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It was found that under all conditions listed in Table 6.3, position sensing was possible with identical feedback system parameters. Therefore, it can be stated as a general conclusion that the up-hill sensing approach offers a reliable tool for seam tracking during GTA welding, which can be successfully used in a wide range of applications.

6.3 Conclusions

This chapter deals with the applicability of additives, in particular SiO₂, during GTA welding. It can be concluded that:

• addition of SiO₂ leads to an increase in weld penetration both in the case of mild steel (Fe360) and in the case of stainless steel (AISI304);
• the use of SiO₂ during GTA welding reduces the problem of varying weld penetration due to cast-to-cast variations in stainless steel;
• the use of SiO₂ during GTA welding makes it possible to achieve full penetration with lower heat input;
• the influence of SiO₂ on arc voltage can be used as a tool for position sensing during GTA welding;
• up-hill sensing is the most promising approach for seam tracking.
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APPENDIX A

POSITIVE IONIZATION

A.1 Introduction

In chapter 3 the influence of metal atoms on the electric properties of the welding arc is referred to as a possible cause of the influence of additives on the properties of the welding arc. In this appendix, a theoretical approach of the influence of metal atoms on the welding arc is given. In section A.2 attention will be paid to the influence of metal atoms on the arc column, while in section A.3 the influence in the fall regions will be discussed.

A.2 The arc column

The conductivity of a gas of arbitrary degree of ionization can be expressed by the equation [A.1-A.5]:

\[
\sigma = \frac{0.532e^2}{(m_e kT)^{3/2}} \frac{n_i}{n_i Q_i + n_s Q_s} \tag{A-1}
\]

In this equation \( Q_i \) is the collision cross-section for electron-ion interactions, which is defined by:
\[ Q_i = \frac{4.1 \times 10^{-6}}{T^2} \left( \ln \left( \frac{T}{n_e^{1/3}} \right) + 5.68 \right) \text{cm}^2 \] (A-2)

\( Q_a \) is the collision cross-section for electron-atom interactions. Values of \( Q_a \) are species dependent and some values are determined experimentally. For metals, \( Q_a \) is in the order of \( 10^{-14} \text{ cm}^2 \), for argon \( Q_a \) is in the order of \( 10^{-17} \text{ cm}^2 \) [A.6].

Values of \( n_i \), \( n_a \) and \( n_e \) can be calculated using the equation of Saha:

\[ \frac{n_e}{n_a} = \frac{Z_e Z_i}{Z_a} \left( \frac{2 \pi m_e k T}{\hbar^2} \right)^{3/2} e^{-\nu/kT} \] (A-3)

With the help of equation (A-1) the electrical conductivity as function of the temperature can be calculated for plasmas of different composition, using appropriate values of \( Q_i \), \( Q_a \), \( T \), \( n_e \), \( n_i \) and \( n_a \). As an example, the electrical conductivity of a pure argon plasma, an argon plasma with iron and an argon plasma with iron and silicon was calculated. The results are shown in Chapter 3, Fig. 3.15.

It can be seen in this figure that the presence of a small amount of an additional element hardly influences the electrical conductivity of the arc column of the welding arc, which in this case is approximated by an argon-iron plasma.

### A.3 Fall regions

An appropriate way to express the influence of metal ions on the electrical properties of the fall regions, is to compare the electrical field strength without and with metal atoms.

According to Poisson’s law, the change in electrical field strength with distance is given by:

\[ \frac{dE}{dx} = 4 \pi e n_x \] (A-4)

With \( j_x = n_x e v_x \), \( v = \sqrt{\frac{2eV}{m_x}} \) and \( V = Ex \) this equation becomes:

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\[ \sqrt{E} \frac{dE}{dx} = 4\pi j_x \frac{\sqrt{m_x}}{2e^{*}} \frac{1}{\sqrt{x}} \, dx \]  \hspace{1cm} (A-5)

This equation can easily be integrated, which results in:

\[ E^2 = 12\pi \sqrt{V} j_x \frac{\sqrt{m_x}}{2e} \]  \hspace{1cm} (A-6)

In this equation the effects of additional ions can be introduced, after which the electric field strength with and without ions can be compared.

A.3.1 Anode fall region

In the anode fall region a negative space charge (electrons) exists and Poisson’s law can be expressed by:

\[ \frac{dE}{dx} = 4\pi e n_e \]  \hspace{1cm} (A-7)

When positive ions are added, this equation becomes:

\[ \frac{dE}{dx} = 4\pi e \left| n_e - n_+ \right| \]  \hspace{1cm} (A-8)

Under these conditions Eq. A-6 can be written as:

\[ E_{sp}^2 = 12\pi \sqrt{V/2e} \left| j_e \sqrt{m_e} - j_+ \sqrt{m_+} \right| \]  \hspace{1cm} (A-9)

The ratio between the original electric field strength \( E_{ao} \) and the new electric field strength \( E_{ap} \) can now be expressed as follows:

\[ \frac{E_{ap}}{E_{ao}} = \sqrt{1 - \left( \left( j_+ / j_e \right) \sqrt{m_+/m_e} \right)^2} \]  \hspace{1cm} (A-10)

By plotting \( E_{ap}/E_{ao} \) against \( j_+ / j_e \) (Chapter 3, Fig. 3.16), the influence of positive ions on the electric field strength in the anode fall region can be estimated. It should be kept in mind that under normal welding conditions, Fe\(^+\) ions are already present in the arc. Addition of
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SiO₂ will presumably cause a replacement of Fe⁺ ions by Si⁺ ions. Hence, two situations at the same value of $j_e/j_e$ should be compared. As mentioned before, a negative space charge exists in the anode fall area: the ratio $j_e/j_e$ will be small. Therefore, the replacement of Fe⁺ ions by Si⁺ ions will hardly influence the voltage in the anode fall region.

A.3.2 Cathode fall region

Normally, it is assumed that the electric field strength in the cathode fall region is generated by positive ions and electrons. As stated before, a positive space charge exists. In the case of welding with additives (SiO₂), part of the originally present positive ions will be replaced by ions originating from the additive. The influence of this replacement on the electric field strength in the cathode fall region can be calculated in a way, analogous to that for the anode fall region. It appears that the influence of ion exchange is negligibly small.

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APPENDIX B

NEGATIVE IONIZATION

B.1 Introduction

In Chapter 3 the influence of molecules and negative ions on the electric properties of the welding arc is referred to as a possible cause of the influence of additives on the electric welding arc. In this appendix, a theoretical approach of the influence of these particles on the welding arc is given [B.1-B.4]. In section B.2 attention will be paid to the influence of negative ions on the arc column, while in section B.3 the influence on the fall regions will be discussed.

B.2 The arc column

As stated before, local thermodynamic equilibrium exists in the column of the arc and the number of electrons equals the number of positive ions. In the central region of the arc column, the temperature is high enough to dissociate and ionize the present molecules. In the outer, cooler regions of the arc column, however, the vaporized materials will still exist as molecules and dissociated atoms.

Generally speaking, the particles in the outer regions of the arc, originating from for example an additive, are able to catch electrons forming negatively charged ions. As a result, the number of electrons, which are the main charge carriers, will decrease. This forces the arc column to constrict to a new equilibrium with higher current density, which
will in turn raise the electric field strength (to maintain the electric current) and, hence, the voltage in the arc column. The degree of constriction depends on the efficiency of the molecules in capturing electrons.

**B.3 Fall regions**

The influence of negatively charged ions on the electric properties of the fall regions can be approached in the same way as the influence of positively charged ions on the fall regions. Thus, use is made of Poisson’s law.

**B.3.1 Anode fall region**

In the anode fall region a negative space charge exist and Poisson’s law becomes:

\[
\frac{dE}{dx} = 4\pi en_e
\]  
(B-1)

In case of positive ions present, this equation can be written as:

\[
\frac{dE}{dx} = 4\pi e(n_e + n_-)
\]  
(B-2)

This leads to (see Appendix A):

\[
E_{an}^2 = 12\pi\sqrt{V/2e}(j_e\sqrt{m_e} + j_-\sqrt{m_-})
\]  
(B-3)

The ratio $E_{an}/E_{a0}$ can now be expressed as:

\[
\frac{E_{an}}{E_{a0}} = \sqrt{1 + \left(\frac{j_-}{j_e}\right)\sqrt{m_-/m_e}}
\]  
(B-4)
In Fig. 3.18 (Chapter 3) \( \frac{E_{an}}{E_{ao}} \) is plotted versus \( j_0/j_e \). It can be seen in this figure, that even at small values of \( j_0/j_e \), the value of \( E_{an}/E_{ao} \), and hence the arc voltage, can become significantly higher. Thus, the presence of negatively charged ions is expected to have a large impact on the anode fall region.

**B.3.2 Cathode fall region**

In a similar way as described above, the influence of negative ions on the voltage in the cathode fall region can be calculated. It appears that only in the case of a large number of negative ions present, the influence will be noticeable. However, this is very unlikely to be the case, as the negative cathode will repulse the negatively charged particles.

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The measurement of the surface tension under arc welding conditions

An appropriate way to determine the surface tension of the liquid metal in the weld pool, is to determine the frequency of the natural oscillation of the weld pool. The oscillation behavior of the weld pool has been the subject of research for several years. In this research it was shown that the relationship between the surface tension of the liquid weld metal and the oscillation frequency of the weld pool for partially penetrated circular weld pools can be expressed as [C.1, C.2]:

\[ f^2 = \frac{1}{4\pi^2} \left( \frac{11.04}{d} g + \frac{1345}{d^3} \frac{\gamma}{\rho_1} \right) \tanh \left( 22.08 \frac{D}{d} \right) \quad (C-1) \]

with \( f \) the oscillation frequency, \( d \) the weld pool diameter, \( g \) the gravitational constant, \( \gamma \) the surface tension, \( \rho \) the liquid density and \( D \) the weld pool depth.

In real welding processes \( D > 0.2d \), which allows the simplification \( \tanh(22.08D/d) = 1 \). Furthermore, it appears that for small weld pools the influence of the gravitational force can be neglected. This leads to the simplified expression [C.3]:

\[ f = 5.84 \left( \frac{\gamma}{\rho_1} \right)^{1/2} d^{-3/2} \quad (C-2) \]
Appendix C

The oscillation frequency $f$ can be determined by superimposing a current peak over the welding current, and subsequently measuring and analyzing the voltage variations caused by the resulting weld pool oscillation [C.4, C.5]. The diameter of the weld pool can be measured after solidification of the pool. With the help of Eq. (C-2) the surface tension can be determined.

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SUMMARY

Since the discovery of the electric arc in 1801, much research has been carried out in the field of the joining of metals with the aim to develop new welding processes. This resulted in a wide variety of arc welding processes, which are now indispensable for joining metals in industrial applications. Recently, research has developed a tendency to focus on the improvement and automation of existing welding processes. This thesis deals with the application of additives during Gas Tungsten Arc welding and, hence, links seamlessly up with this tendency.

The first advantage of applying additives in GTA welding is based on the fact that the different additives, and especially SiO₂, cause an improvement in weld penetration. For example, the depth-to-width (D/W) ratio of a weld can be increased to up to 200% at lower currents and up to 300% at higher currents with respect to normal D/W ratios of welds in both stainless steel (AISI304) and mild steel (Fe360). Furthermore, it appears that the application of SiO₂ leads to an almost complete elimination of variations in weld penetration, which normally are likely to occur due to cast-to-cast variations in stainless steel.

The weld penetration improvement can be used to achieve full penetration in thick plates in a single pass. For example, stainless steel and mild steel plates of 5 mm thickness can be welded in a single pass with a welding current of 150 A and 140 A, respectively, while in the case of using the standard GTA welding process this is hardly possible because of unpredictable broadening and sagging of the weld. Another advantage of applying SiO₂ is the possibility of producing full penetration welds with lower heat input, which means that a lower welding current or a higher travel speed can be applied.
Summary

The second application of additives is that they can be used for position sensing during GTA welding. It appears that different additives, and especially oxides, influence the arc configuration, resulting in a measurable increase in arc voltage. By marking the seam before welding and monitoring the arc voltage continuously during welding, it can be decided at any moment whether the arc is in the right position.

In principle, two approaches exist for additive-assisted position sensing during GTA welding. The first approach, up-hill sensing, utilizes the increase in arc voltage when the arc runs into a zone covered with SiO₂. The second approach, down-hill sensing, uses the decrease in arc voltage when the arc leaves an additive covered zone. It appears that up-hill sensing is the most promising tool for position sensing.

A major part of this thesis is formed by the study of the changes in arc properties and weld pool configuration when welding with additives, including the mechanisms that cause these changes. To be able to determine which aspects and parameters of the GTA welding process are of importance in this approach, first the general features of this process were studied. This resulted in the conclusion that both arc and weld pool processes can be strongly influenced by the application of additives, and that it is useful to study these influences separately, because of the complexity of the welding process.

The results show that additives influence the electric properties of the welding arc resulting in a change in arc voltage. The largest influence on arc voltage was found when using SiO₂ as additive. It appears that SiO₂ affects both the arc column and the fall regions. The influence on arc voltage increases with increasing arc length and travel speed and decreases with increasing welding current.

Using the results of a large number of welding experiments in combination with optical photography and spectroscopic measurements, it was shown that the observed effects can be explained in terms of arc contraction by negative ion formation. In addition, dissociation and arc trailing both account for a small part of the effect on arc voltage. Positive ion formation plays a negligible role.

In a similar way, the effect of additives on weld pool formation was dealt with. Firstly, a series of preliminary experiments was carried out aimed at evaluating the influence of a number of different additives on the weld pool. It was found that especially oxides (particularly SiO₂) cause an increase in weld pool penetration. To be able to determine which mechanisms cause the improved penetration, a parameter study was carried out with
SiO$_2$ as additive, in which the width, depth and length of the weld pool were determined as a function of welding current, travel speed and arc length. It appears that the effect of SiO$_2$ on weld penetration increases with travel speed, welding current and arc length. In addition, the surface tension of the liquid metal in the weld pool without and with SiO$_2$ was determined.

From the results it can be concluded that the improved penetration is caused by two mechanisms: contraction of the contact area between arc and weld pool and changes in the weld pool flow due to the enlarged Lorentz force acting on the liquid weld metal.

The influence of SiO$_2$ on the chemical composition, the microstructure and the mechanical properties was also studied. It appears that the addition of SiO$_2$ leads to a small increase of the silicon and oxygen content of the weld and to a significant change in the microstructure of the weld. In the weld metal more grain boundary ferrite and less acicular ferrite is formed, whereas in the fine-grained zone of the HAZ the grain size appears to be larger in case of welding with SiO$_2$, resulting in a coarser structure. Furthermore, it appears that SiO$_2$ addition results in a lower hardness of the weld metal, while the strength is hardly affected. The observed changes in the microstructure and the mechanical properties can be explained in terms of the change in heat input (cooling rate) caused by SiO$_2$ addition.

Wilma Middel
22 september 2000
SAMENVATTING

Sinds de ontdekking van de elektrische boog in 1801 is er veel onderzoek verricht op het gebied van het verbinden van metalen. In eerste instantie was het doel van het onderzoek het ontwikkelen van nieuwe lasprocessen. Dit heeft geresulteerd in een breed spectrum aan booglasprocessen die in de industrie inmiddels onmisbaar zijn voor het verbinden van metalen. Recentelijk heeft zich een tendens ontwikkeld waarbij het onderzoek zich vooral richt op de verbetering en de automatisering van bestaande processen. In dit proefschrift wordt het onderzoek naar de mogelijkheid om met behulp van additieven het rendement van het TIG-lasproces te verbeteren beschreven. Daarnaast wordt aandacht besteed aan de haalbaarheid van een nieuw naadvolgsysteem gebaseerd op het gebruik van additieven. Hiermee sluit dit proefschrift naadloos aan op de bovengenoemde tendens.

Een belangrijke toepassing van het gebruik van additieven tijdens TIG-lassen is gelegen in het feit dat de verschillende additieven, en in het bijzonder SiO₂, een verbetering in de inbranding veroorzaken. De diepte-breedte verhouding van een las kan door het gebruik van additieven bijvoorbeeld twee keer zo groot worden bij lagere stroomsterktes en zelfs drie keer zo groot bij hogere stroomsterktes. Dit geldt voor zowel roestvast staal (AISI304) als koolstofstaal (Fe360). Daarnaast blijkt dat door het gebruik van SiO₂ de variaties in de inbranding (een verschijnsel dat wordt veroorzaakt door variaties in de chemische samenstelling van het basismateriaal) bijna volledig verdwijnen.

De penetratieverbetering kan worden gebruikt om in één keer een volledige doorlasing in dik plaatmateriaal te creëren. Platen roestvast staal en koolstofstaal van 5 mm dik kunnen bijvoorbeeld in één keer worden doorgelast met een lasstroom van respectievelijk 150 en 140 A. Normaliter is dit onmogelijk omdat bij de vereiste stroomsterkte een onvoorspelbare verbreding van het lasbad optreedt en doorzakken van de las niet te vermijden valt. De penetratieverbetering die wordt veroorzaakt door de toepassing van SiO₂ kan natuurlijk ook gebruikt worden om dunner plaatmateriaal door te lassen bij een
Samenvatting

lagere warmte-inbreng. Zo is voor het doorlachen van roestvast staal platen van 3 mm dik
normaal een lasstroom van 110 A nodig. Door het gebruik van SiO₂ kan de lasstroom van
110 A worden verlaagd naar 80 A. In plaats van het verlagen van de lasstroom, zou ook de
voortloopsnelheid tijdens het lassen kunnen worden verhoogd.

Een tweede toepassing van additieven is dat ze kunnen worden ingezet voor plaatsbepaling
en naadvolgen tijdens TIG-lassen. Verschillende additieven, in het bijzonder oxides,
blijken de boogconfiguratie te beïnvloeden. Dit resulteert in een meetbare verhoging van de
boogspanning. Door de lasnaad vóór het lassen te markeren met een geschikt additief en de
boogspanning continu te meten tijdens het lassen kan zo op elk moment bepaald worden of
de boog zich op de juiste plaats bevindt.

In principe zijn er twee benaderingen voor het additief-ondersteund naadvolgen tijdens
TIG-lassen. Bij de eerste benadering, up-hill sensing, wordt gebruik gemaakt van de
verhoging van de boogspanning die optreedt wanneer de boog tegen een met additief
bedekte zone aanloopt. Bij de tweede benadering, down-hill sensing, wordt gebruik
gemaakt van de boogspanningsverlaging die optreedt wanneer de boog van een met
additief bedekte zone afloopt. Onderzoek wijst uit dat up-hill sensing het meest geschikt is
voor naadvolgen.

Een groot deel van dit proefschrift in gewijdt aan het onderzoek van de veranderingen in de
eigenschappen van de boog en het lasbad ten gevolge van het lassen met additieven,
inclusief de mechanismen die de veranderingen veroorzaken. Om te bepalen welke
aspecten en parameters van het TIG-lasproces hierbij van belang zijn, werden eerst de
algemene eigenschappen van het proces bestudeerd. Hieruit bleek dat zowel de boog als het
lasbad beïnvloed kunnen worden door de toepassing van additieven. Vanwege de
complexiteit van het lasproces werd besloten de invloed van additieven op de lasboog en
het lasbad afzonderlijk te onderzoeken.

Om de invloed van additieven op de lasboog te bepalen werd een serie experimenten
uitgevoerd met verschillende additieven. De resultaten laten zien dat de additieven vooral
de elektrische eigenschappen van de boog beïnvloeden, hetgeen resulteert in een
verandering in de boogspanning. De grootste invloed werd gevonden bij toepassing van
SiO₂. De invloed van SiO₂ op de boogspanning neemt toe met de booglengte en de
voortloopsnelheid. Het effect wordt minder met toenemende stroomsterkte.
Op basis van de resultaten van een groot aantal lasexperimenten in combinatie met optische fotografie en spectroscopische metingen kon worden aangetoond dat de boogspanningsverhoging veroorzaakt wordt door een aantal mechanismen. Boogcontractie als gevolg van negatieve ionvorming blijkt het grootste aandeel te hebben in de boogspanningsverhoging. Daarnaast dragen dissociatie en ‘trailing’ van de boog bij aan de verandering van de boogspanning. De vorming van positieve ionen heeft nauwelijks invloed op de boogspanning.

Additieven hebben ook een belangrijke invloed op het lasbad. Om de invloed van verschillende additieven op het lasbad te bepalen werd een aantal experimenten uitgevoerd. Hieruit bleek dat vooral oxides (SiO₂) een grote invloed hebben op de lasbadvorming. Om de verkregen resultaten te kunnen verklaren werden extra experimenten uitgevoerd met SiO₂, waarbij de breedte, diepte en lengte van het lasbad werden bepaald als functie van de lasstroom, de booglengte en de voortlooppnelheid. Uit de experimenten bleek dat het effect van SiO₂ op de inbranding toeneemt met zowel de voortlooppnelheid als de lasstroom en de booglengte. Bij andere experimenten werd de oppervlaktespanning van het vloeibare metaal in het lasbad bepaald in af- en aanwezigheid van SiO₂ als functie van de temperatuur.

Op basis van de resultaten kon worden geconcludeerd dat de verbeterde inbranding wordt veroorzaakt door twee verschijnselen: enerzijds door de contractie van het contactoppervlak tussen de boog en het bad en anderzijds door de toename van de Lorentzkracht die een toename in de (naar binnen gerichte) Lorentzstroming in het lasbad tot gevolg heeft.

Tenslotte werd de invloed van SiO₂ toevoeging op de chemische samenstelling, de microstructuur en de mechanische eigenschappen van de las bestudeerd. De toevoeging leidt tot een kleine toename in de concentratie van silicium en zuurstof in het lasmetaal en tot een significante verandering in de microstructuur van de las. In het lasmetaal wordt meer korrelgrensferrit en minder naaldferrit gevormd, terwijl in de warmtebeïnvloede zone grotere korrels worden gevormd, resulterend in een grovere structuur. Daarnaast blijkt dat door toevoeging van SiO₂ de Vickers hardheid van de las iets afneemt, terwijl de sterkste nauwelijks verandert. Deze veranderingen kunnen worden toegeschreven aan de veranderingen in de warmte-inbreng die de toevoeging van SiO₂ met zich meebrengt.

Wilma Middel
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Samenvatting
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