Welding Technology

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Preface

Over the years a large number of techniques has been developed to join materials. Well known joining techniques are soldering, brazing, adhesive joining and welding, each playing an important role in the present manufacturing industry. In particular welding is applied on a wide scale, ranging from small products to large industrial constructions.
In welding the parts to be joined are heated, sometimes in combination with the application of pressure. The necessary heat can be provided by various sources. Use can be made, for instance, of heat produced by electric current passage, by chemical reactions, by radiation and by friction.

Usually, a distinction is made between fusion welding and solid state welding.
The essential feature of fusion welding is that local melting of the material(s) takes place during the welding process followed by solidification, whereas in the case of solid state welding no melting takes place and the weld is formed by plastic deformation and solid state reactions.

During welding the material to be welded is subjected to a thermal cycle, consisting of rapid heating, followed by relatively slow cooling. As a result of this thermal cycle different physical and chemical reactions take place in the liquid and solid phase, which are decisive for the properties of the welded joint.

This textbook deals with the different aspects of welding and is based on courses given at Delft University of Technology in the period 1980 - 2008.
It is intended primarily for undergraduate and graduate students in materials science and mechanical engineering, but may also provide useful background information to engineers and researchers, who are professionally involved in welding.

The book is divided into three parts.
In Part I (Processes) the most important welding processes applied in industry are addressed. Specific attention is given to arc welding (Chapter 1), whereas a number of other processes are reviewed in Chapter 2.
Part II (Metallurgical aspects) deals with the effect of the thermal cycle due to welding on the structure and properties of the welded joint, including the development of residual stresses.
In Part III (Applications) the possibilities and limitations of welding carbon and low-alloy steel (Chapter 4), stainless steel (Chapter 5) and aluminium (Chapter 6) are discussed. Chapter 7 deals with non-destructive testing of welded joints.

The authors like to thank the publisher J.E. Schievink of VSSD for his support and patience during the preparation of the book.
Comments on the book are welcome.

G. den Ouden
M.J.M. Hermans

Delft, 2009

Contents

List of symbols and units

symbol	description	unit
c	constant	-
c_a, c_c	fraction	-
e	electron charge	C
d	distance, diameter, thickness	m
g	gravitational acceleration	m s^{-2}
j	current density	A m^{-2}
j_e	electron current density	A m^{-2}
j_i	ion current density	A m^{-2}
k	Boltzmann constant	J K^{-1}
l	arc length	m
$l_{e/I}$	free path length (electron/ion)	m
m	mass	kg
m_e	mass of electron	kg
m_i	mass of ion	kg
n_e	electron density	m^{-3}
n_i	ion density	m^{-3}
p	gas pressure	Pa
q	electric charge	C
q	quantity of heat or energy	J
r	radius	m
t	time	s
t_b	base time	s
t_p	pulse time	s
t_e	time between collisions electron	s
$\bar{u}_e$	average drift velocity of electron	m s^{-1}
v	travel speed, velocity	m s^{-1}
x, y, z	axial coordinates	m
A	constant	
A	area	m^2
C_1	constant	
B	magnetic induction	Nm^2A^{-1}
C_2	constant	
C_p	specific heat	J kg^{-1} K^{-1}
D	diffusion coefficient	m^2s^{-1}
E	electric field strength	V m^{-1}
E_d	dissociation energy	eV
E_i	ionisation energy	eV

F	force	N
F_L	Lorentz force	N
H	energy to heat and melt a unit mass	J kg^{-1}
I	radiation intensity	
I	welding current	A
I_b	base current	A
I_{cr}	critical current globular-spray transfer	A
I_p	peak current	A
M	melting rate	kg s^{-1}
M	mixing ratio	-
L	electrode stick-out length	m
Q	amount of heat or energy	J
Q_a	heat transferred to anode per unit time	Js^{-1}
Q_c	heat transferred to cathode per unit time	Js^{-1}
Q_j	Joule heat	J
R	electric resistance	Ω
T	temperature	K
T_a	anode temperature	K
T_c	cathode temperature	K
T_{col}	column temperature	K
T_e	electron temperature	K
T_g	gas (atom/ion/molecule) temperature	K
T_m	melting point	K
V	arc voltage	V
V_a	anode fall voltage	V
V_c	cathode fall voltage	V
V_{col}	column voltage	V
V_B	breakdown voltage	V
W	heat input	J m^{-1}
Z	atomic number	-
α	avalanche factor	V^{-1}
α_d	degree of dissociation	-
α_i	degree of ionisation	-
φ	threshold potential electron emission	V
φ_c	threshold potential electron emission from cathode	V
φ_a	potential for electron absorption at anode	V
κ	heat transfer coefficient	W m^{-1} K^{-1}
λ	wave length	m
μ_o	permeability of free space	H m^{-1}
η_p	process efficiency	-
η_m	melting efficiency	-
γ	probability factor	-
γ	surface tension	N m^{-1}
ρ	electric resistivity	Ω m
ρ	mass density	kg m^{-3}
σ	electric conductivity	Ω^{-1} m^{-1}

I PROCESSES

1 Arc Welding

1.1 Introduction

Under normal conditions gases are poor conductors of electricity, due to the fact that they contain no free charge carriers (electrons/ions) needed for the current flow. However, when sufficient energy is supplied to the gas, the atoms or molecules will ionize, generating free electrons and ions and making conduction possible.

The phenomenon of electric conduction by gases has been known for a long time. It is manifest in a number of different forms, referred to by the somewhat misleading name gas discharge. Examples of gas discharges are spark, lightning, Townsend discharge, glow discharge and arc discharge. Spark and lightning are momentary, non-stationary types of discharge; their maximum lifespan is around 10^{-2} s. The Townsend discharge, glow discharge and arc discharge are stationary types of discharge, which can exist for indefinite time. The different types of gas discharge can be distinguished by their voltage-current characteristic, as shown in Figure 1.1.

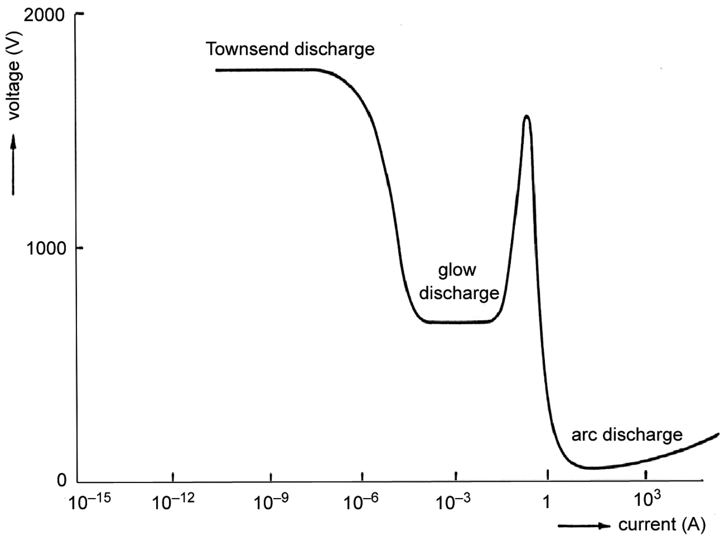

Figure 1.1. Voltage-current characteristic of different types of gas discharge.

The Townsend discharge is characterized by a high voltage (kilovolts) and a very low current (micro-amperes). A high resistance in the circuit is required to maintain this type of discharge.
The glow discharge is characterized by a lower voltage (hundreds of volts) and a higher current (milli-amperes). With this discharge a positive space charge is formed just in front of the cathode, which leads to a strong increase of the electric field.
In the case of the arc discharge, space charges also play an essential role. The voltage is lower than in the case of a glow discharge (tens of volts), while the current is much higher (amperes).
The arc discharge is characterized by a wide power range, which makes it suitable for a variety of industrial applications, such as welding, cutting and furnace heating.

This chapter deals with arc welding. First, the most important properties of the arc discharge will be discussed. In the second part of the chapter, the application of the arc discharge in the arc welding process will be considered.

1.2 General characteristics of the arc

As noted above, the arc discharge (from now on simply referred to as 'arc'), is characterized by a relatively low voltage and a relatively high current. A typical current-voltage characteristic is presented in Figure 1.2. The figure shows that the voltage initially drops rapidly with current and starts to rise slightly when the current is further increased. The energy developed in the arc per unit time equals $V \times I$, where V is the arc voltage and I the current. Under stationary conditions, this energy equals the energy disappearing per unit time from the arc by conduction, convection and radiation of heat.

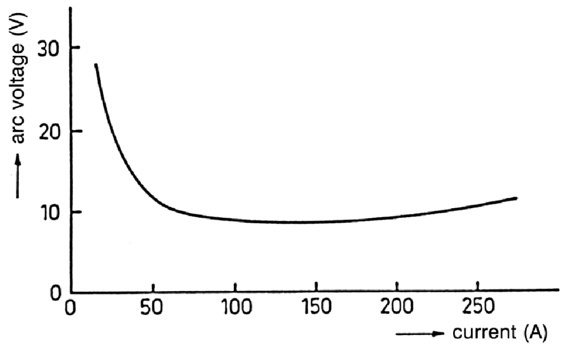

Figure 1.2. Voltage-current characteristic of the arc.

The arc derives its name from the shape of the hot gas when the electrodes are placed horizontally with respect to each other (Figure 1.3): because of its lower density, the hot gas will tend to rise, forming an arc shape as a result. This effect can be observed especially when using thin, rod-shaped electrodes placed horizontally at a relatively large distance. Under practical arc welding condition, this distance is usually small (between 0.1 and 1 cm), and only one of the electrodes is rod-shaped, the other one being usually flat (workpiece). In that case the arc is almost always bell-shaped (see Figure 1.4).

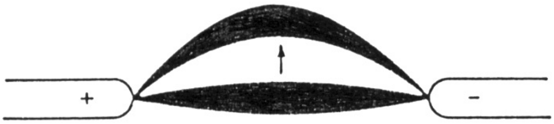

Figure 1.3. Formation of the arc shape in the case of rod-shaped electrodes, placed horizontally at large distance.

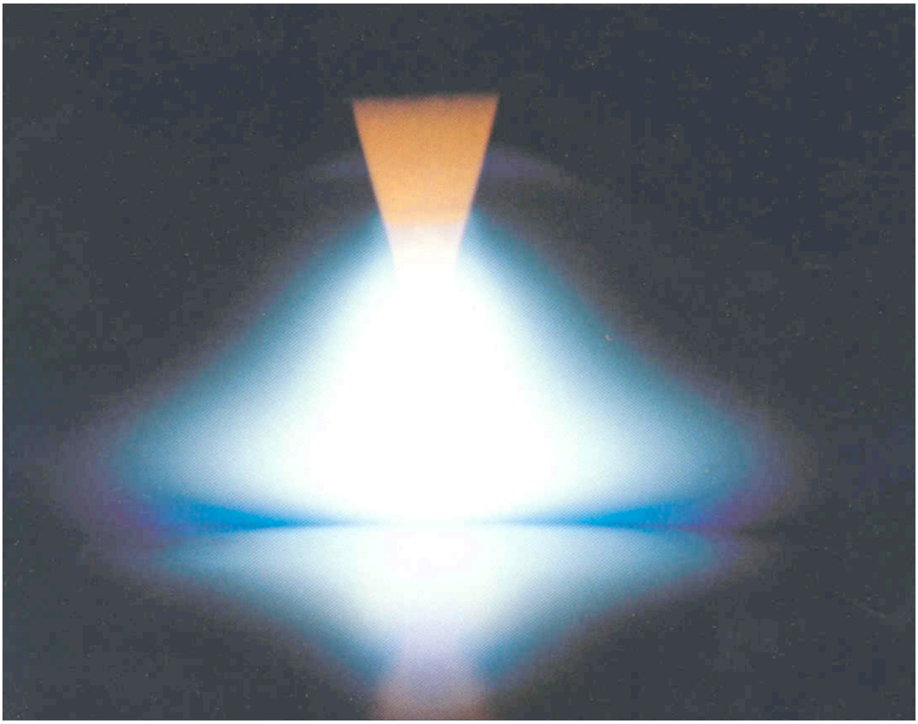

Figure 1.4. Bell-shaped arc.

Measurements show that the arc voltage is not a linear function of the distance between the electrodes, but is characterized by voltage drops close to the electrodes. These voltage drops are caused by the presence of space charge in the vicinity of the electrodes, as will be shown later. The voltage distribution in the arc is shown schematically in Figure 1.5.

Usually the arc is divided in three separate regions, each with its own physical properties. By far the largest space between the electrodes is occupied by the arc column, which is characterized by a small and constant voltage gradient. Adjacent to the electrodes are the so-called fall zones, characterized by voltage drops: the cathode fall zone in front of the cathode (negative electrode), and the anode fall zone in front of the anode (positive electrode). In the following sections, these three arc regions will be discussed separately.

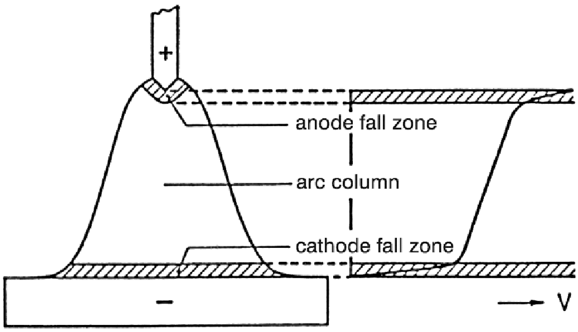

Figure 1.5. Voltage distribution in the arc.

1.3 The arc column

The arc column is composed of neutral particles, such as atoms and molecules (both in the excited and in the non-excited state), and electrically charged particles, such as electrons and ions. The electrons and negative ions move towards the anode under the influence of the electric field, while the positive ions move towards the cathode.
An important property of the arc column is its electric neutrality: each volume unit of the column contains equal numbers of positive and negative electric charge carriers. This condition is often referred to as a plasma. A consequence of the electric neutrality, and hence the absence of space charge, is the presence of a constant electric field in the arc column. This follows directly from Poisson's law:

$$\frac{d^2V}{dx^2} = \frac{dE}{dx} = -4\pi q \tag{1.1}$$

where V denotes the voltage, x the axial coordinate between anode and cathode, E the electric field strength and q the electric charge per unit volume. The electric field strength in the column has a typical value of 10 Vcm^{-1}.
Another important property of the arc column is its local thermal equilibrium. This means that, by mutual collisions, complete exchange of energy takes place between the different particles. Consequently, all particles obtain approximately the same

average kinetic energy, or:

$$\frac{1}{2} m_1 \overline{v_1^2} = \frac{1}{2} m_2 \overline{v_2^2} = \ldots = \frac{1}{2} m_j \overline{v_j^2} = \frac{3}{2} kT \qquad (1.2)$$

where m_j and v_j represent the mass and velocity of a particle j, k represents the Boltzmann constant, and T represents the absolute temperature. As the plasma consists of electrons and heavier particles a distinction can be made between the electron temperature T_e and the gas temperature (ion/atom/molecule temperature) T_g. In the case of thermal equilibrium, both temperatures are equal. In the arc column however, T_e is always somewhat higher than T_g, due to the fact that in the time interval between two consecutive collisions, electron drift takes place and the electrons will gain more energy from the electric field than the ions, because of their longer free path length. It is therefore better to speak of a quasi-equilibrium. With decreasing pressure the deviation from thermal equilibrium increases and the difference between T_e en T_g becomes significant as illustrated in Figure 1.6.

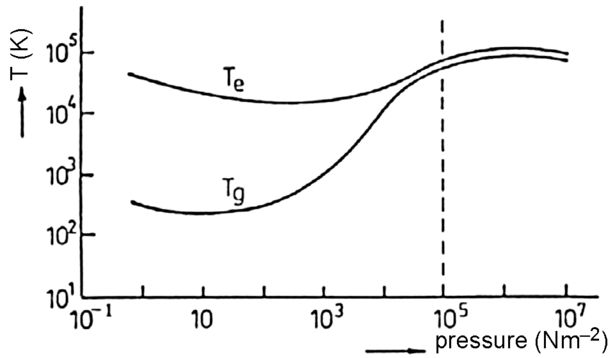

Figure 1.6. Electron temperature (T_e) and gas temperature (T_g) as a function of the pressure.

The foregoing implies that the arc column at atmospheric (or higher) pressure can be characterized by one temperature T ($\sim T_e$, $\sim T_g$). Obviously, this temperature depends on the position in the arc and is determined by the local energy balance: under stationary conditions, the electric energy produced per unit time and unit volume (U_{el}) equals the energy disappearing from that unit volume per unit time by conduction (U_{cond}), radiation (U_{rad}) and convection (U_{conv}), or:

$$U_{el} = U_{cond} + U_{rad} + U_{conv} \qquad (1.3)$$

Calculation of the temperature distribution in the arc column from equation (1.3) is possible in principle, but very complicated in practice, because U_{cond}, U_{rad}, and U_{conv}

are complex functions of T. Nevertheless, equation (1.3) provides valuable information about the temperature distribution.
Measurements indicate that the temperature is maximal in the axis of the arc and decreases rapidly in radial direction. In axial direction the temperature decreases with increasing distance from the electrode.
As an illustration, Figure 1.7 shows the temperature distribution in the column of a 200 A argon arc between a rod-shaped tungsten electrode (cathode) and a water-cooled copper plate (anode). As indicated in the figure, T varies along the axis from approximately 18000 K to around 12000 K. In the case of a welding arc in contact with a liquid weld pool, the column temperature is in general much lower (5000 K to 10000 K). This is due to the presence of metal vapour in the arc (see the sections dealing with ionisation and electric conductivity).
In the arc column, a number of physical phenomena occur. The most important of these will be briefly discussed below.

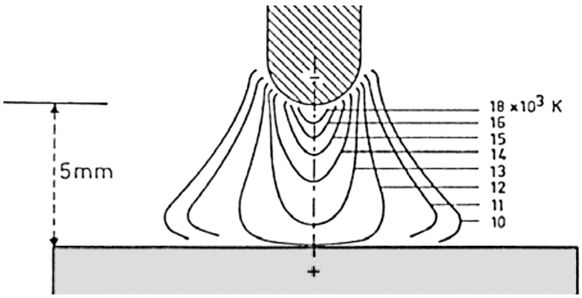

Figure 1.7. Temperature distribution in a 200 A argon arc between a rod-shaped tungsten electrode (cathode) and a water-cooled copper plate (anode).

1.3.1 Ionisation

Ionisation is the process whereby one or more electrons are removed from the atom, yielding positive ions (A^+) and electrons (e). In the case of single ionisation:

$$A + E_{\mathrm{i}} \rightleftarrows A^{+} + e \tag{1.4}$$

with E_{i} the ionisation energy.
In the arc column, part of the atoms or molecules will be ionised under the influence of the temperature. The degree of ionisation α_i is defined as the fraction of the gas in ionised state. The relationship between α_{i} and the temperature T is given by the Eggert-Saha equation:

$$\frac{\alpha_i^2}{1-\alpha_i^2} = C_1 \frac{T^{5/2}}{p} \exp\left(-\frac{E_i}{kT}\right) \tag{1.5}$$

where C_1 represents a constant, p the gas pressure, E_i the ionisation energy of the atom or molecule and k the Boltzmann constant.
The degree of ionisation is plotted as a function of temperature for a number of elements in Figures 1.8 and 1.9, whereas in Figure 1.10 the relation between the degree of ionisation, the ionisation energy and the temperature is shown. Table 1.1 lists the ionisation energy of a number of atoms and molecules.

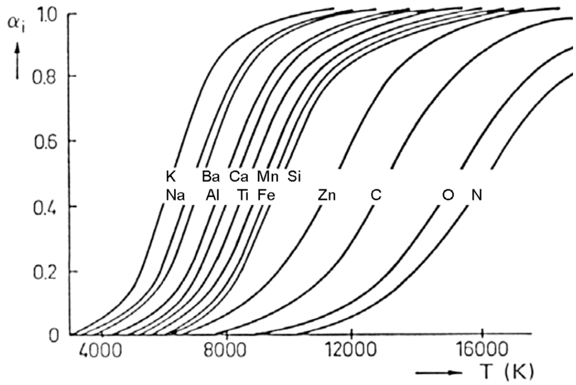

Figure 1.8. The degree of ionisation as a function of temperature for a number of elements.

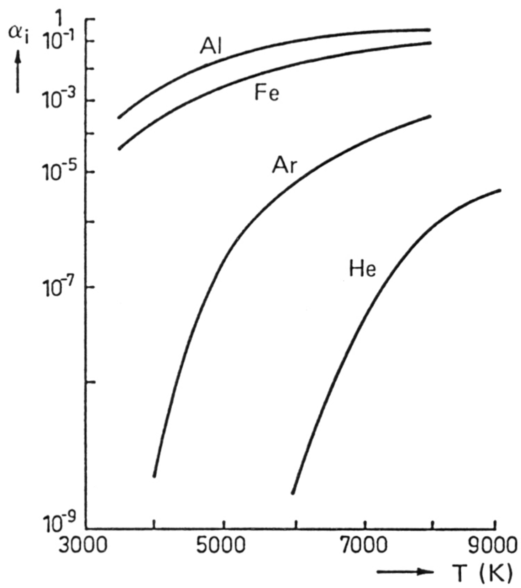

Figure 1.9. The degree of ionisation of Al, Fe, Ar and He as a function of temperature.

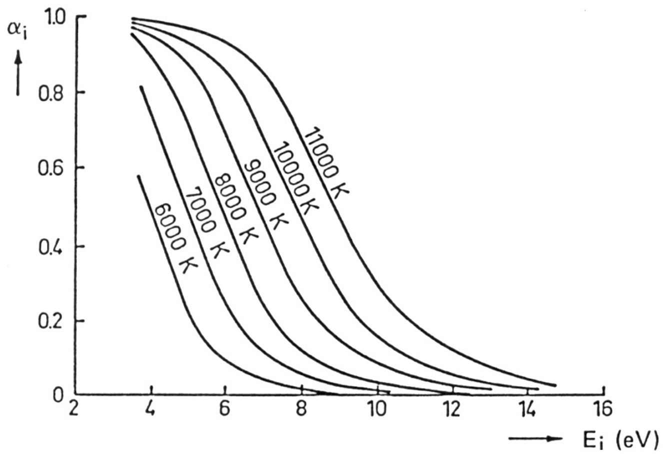

Figure 1.10. The degree of ionisation as a function of ionisation energy for different temperatures.

Table 1.1. Ionisation energy E_i of a number of atoms and molecules.

Element	E_i (eV)	Element	E_i (eV)
H	13.6	P	10.5
H_2	15.6	S	10.4
He	24.6	Ar	15.8
B	8.3	K	4.3
C	11.3	Ca	6.1
CO	14.1	Ti	6.8
CO_2	14.4	Mn	7.4
N	14.5	Fe	7.9
N_2	15.5	Ni	7.6
O	13.6	Cu	7.7
O_2	12.5	Zn	9.4
F	17.4	Zr	6.8
Na	5.1	Mo	7.1
Mg	7.6	Sn	7.3
Al	6.0	W	7.9
Si	8.1	Pb	7.4

The foregoing shows that, due to their lower ionisation energy, metals generally are ionised to a higher degree than non-metals. Iron vapour, for instance, will almost be completely ionised at a temperature of 10000 K, while at that temperature argon is hardly ionised.

This implies that in the case of arc welding, the effective α_i, and therefore the electric conductivity, is almost entirely determined by the present metal vapour (see Section 1.3.3).

It must be noted that ionisation is actually a multi-stage process. This means that with increasing temperature subsequently new electrons will be removed from the atom, until finally only a stripped atom remains. To illustrate the multiple-stage character of the ionisation process, Figure 1.11 shows the particle density of argon as a function of temperature.

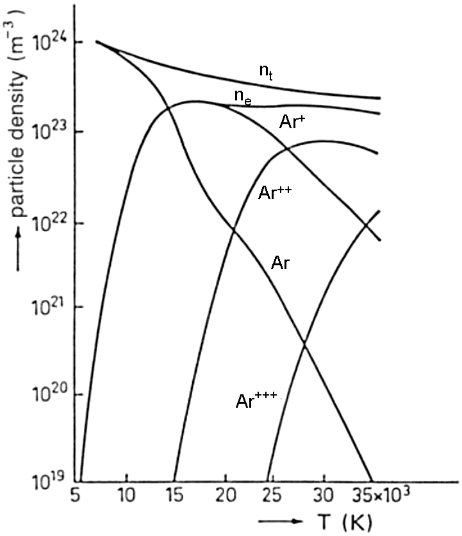

Figure 1.11. Particle density of argon as a function of temperature (n_e represents the electron density, n_t the total particle density).

1.3.2 Dissociation

In the case of a molecular gas (such as H_2, O_2, and N_2), part of the molecules will be dissociated in the arc column under the influence of the temperature. These gases dissociate according to the equation:

$$G_2 + E_d \rightleftarrows 2G \tag{1.6}$$

with E_d the dissociation energy.

The degree of dissociation α_d is defined as the fraction of the gas in dissociated state. The relationship between α_d and the temperature T is given by:

$$\frac{4\alpha_d^2}{1-\alpha_d^2} = C_2 \frac{T^{5/2}}{p} \exp\left(-\frac{E_d}{kT}\right) \tag{1.7}$$

where C_2 represents a constant, p the gas pressure and k the Boltzmann constant.
In Figure 1.12 the relationship between α_d and T is plotted for CO_2 (in equilibrium with $CO + O_2$), H_2, O_2, and N_2. The corresponding values of E_d of these gases are listed in Table 1.2.

Table 1.2. The dissociation energy E_d of some molecular gases.

Gas	H_2	N_2	O_2	CO_2
E_d (eV)	4.48	9.76	5.08	4.3

Given the fact that the temperature in the axis of the arc column generally exceeds 4000 K, it may be concluded from Figure 1.12 that in the case of the gases mentioned, dissociation plays an important role. At 6000 K, for instance, O_2 will be almost completely dissociated, while at this temperature approximately 10% of N_2 will be dissociated.

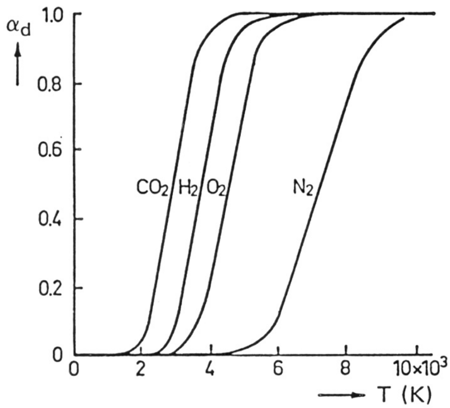

Figure 1.12. The degree of dissociation as a function of temperature for some molecular gases.

It is obvious that dissociation always occurs in combination with ionisation. This is illustrated by Figure 1.13 in which the particle density of nitrogen is plotted as a function of the temperature.

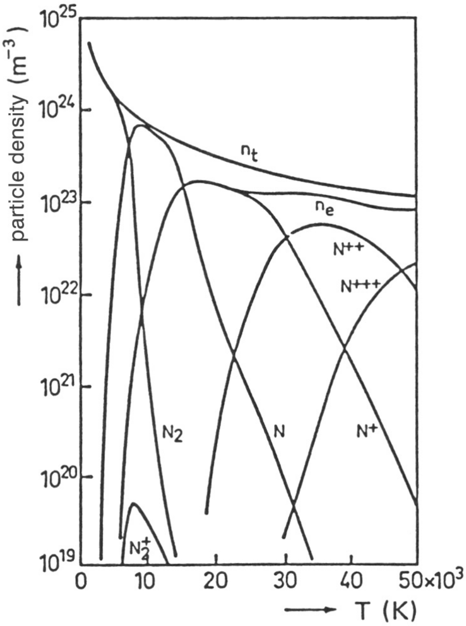

Figure 1.13. Particle density of nitrogen as a function of temperature (n_e represents the number of electrons, n_t the total number of particles).

1.3.3 Electric conductivity

The electric current in the arc column can be considered as the sum of the electron current (from cathode to anode) and the ion current (from anode to cathode). The electron current density j_e (electron current through unit area) is given by:

$$j_e = e\, n_e\, \overline{u}_e \qquad (1.8)$$

where e, n_e, and $\overline{u}_e$ represent the charge, density and average drift velocity of the electron, respectively.

The average drift velocity can be calculated by multiplying the acceleration, which the electrons obtain in the electric field, and the average time t_e between two consecutive collisions, yielding:

$$\overline{u}_e = \frac{eE}{m_e}\,\overline{t}_e \qquad (1.9)$$

Since $\overline{t}_e$ is equal to the quotient of the average free path length $\overline{l}_e$ and the average thermal velocity $\overline{v}_e$, equation 1.9 can be written as:

$$\bar{u}_e = \frac{eE\bar{l}_e}{m_e\bar{v}_e} \tag{1.10}$$

Combining equations (1.2), (1.8) and (1.10), and correcting numerically for the Coulomb interaction between charged particles, results in the following expression for the electron current density in the arc column:

$$j_e = \frac{e^2En_e\bar{l}_e}{\sqrt{8m_ekT/\pi}} \tag{1.11}$$

In a similar way, the following expression for the ion current density can be obtained:

$$j_i = \frac{e^2En_i\bar{l}_i}{\sqrt{8m_ikT/\pi}} \tag{1.12}$$

The ratio between the electron current density and the ion current density can be calculated from equations (1.11) and (1.12). This leads to the following approximate expression:

$$\frac{j_e}{j_i} \approx \sqrt{\frac{m_i}{m_e}} \tag{1.13}$$

As $m_i \gg m_e$, it follows that $j_e \gg j_i$. Apparently, the electron current makes up for the vast majority of the arc current, and the ion current is negligibly small. The electric conductivity σ, defined as the quotient of the current density and the electric field strength, can now be written as:

$$\sigma = \frac{j}{E} = \frac{e^2n_e\bar{l}_e}{\sqrt{8m_ekT/\pi}} \tag{1.14}$$

Because n_e (calculated from α_i) and $\bar{l}_e$ are both unique functions of temperature, σ is determined entirely by T. Figure 1.14 shows the calculated relationship between σ and T for argon. It can be seen that initially σ increases steeply with T and saturation occurs when the gas is fully ionised. Figure 1.15 shows the relationship between the electric resistivity ρ (defined as $1/\sigma$) and T for argon.

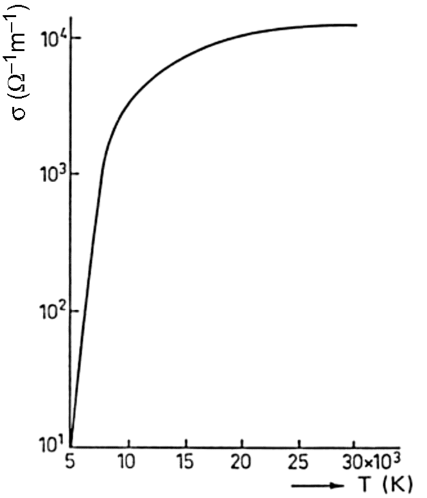

Figure 1.14. The electric conductivity of argon as a function of temperature.

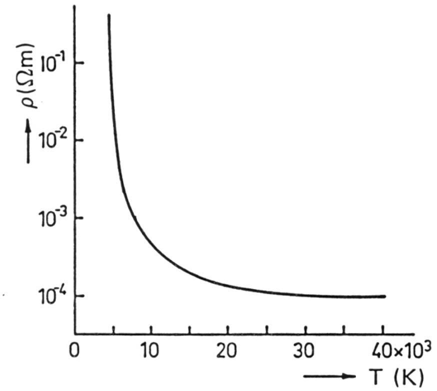

Figure 1.15. The electric resistivity of argon as a function of temperature.

1.3.4 Heat conduction

Heat conduction is usually quantified in terms of the heat transfer coefficient κ, defined as the ratio of the heat flux ΔQ (the heat flowing through a unit area per unit time) and the temperature gradient dT/dx:

$$\Delta Q = \kappa \frac{dT}{dx} \tag{1.15}$$

Different mechanisms contribute to the heat conduction of a plasma. Firstly, heat is transported by mutual collisions of heavy gas particles (atoms, molecules and ions). This transport of heat corresponds with the (classical) heat transfer coefficient κ_g, which can be calculated by means of the kinetic gas theory.

Secondly, heat is transported by collisions between electrons and heavy particles (κ_e); this contribution is relatively small, but becomes increasingly important with rising temperature.

In addition, heat transfer takes place by diffusion of ionised pairs (electrons and positive ions). Hereby, ionisation energy is transferred from the location where the atom/molecule is ionised to the location where recombination takes place (κ_i). Similarly, the diffusion of dissociated pairs in a molecular gas can contribute to the heat conduction (κ_d).

The sum of the individual components constitutes the total heat transfer coefficient. As an example, the components of the heat transfer coefficient for nitrogen are given in Figure 1.16. The κ versus T curve shows two peaks: a dissociation peak at about 7000 K and an ionisation peak at about 15000 K. Obviously, these peaks have an important influence on the temperature profile of the arc.

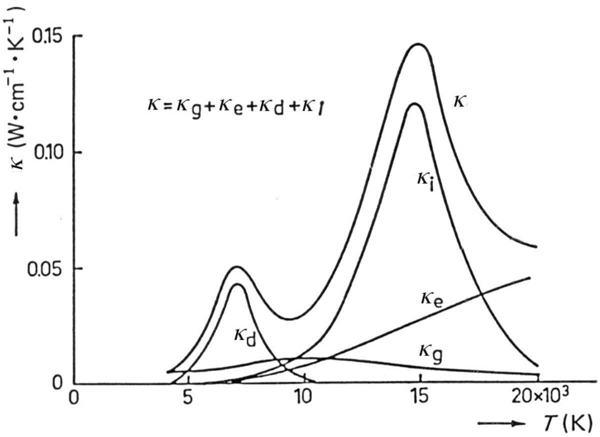

Figure 1.16. The heat transfer coefficient of nitrogen as a function of temperature.

Figure 1.17 shows the calculated temperature profile of an arc in nitrogen. In the calculation only heat conduction has been taken into account and the heat transfer by convection and radiation has been neglected. Note the shoulder in the profile, corresponding with the dissociation peak in heat conduction. In mono-atomic gases, this shoulder is not present, and the temperature profile is more or less parabolic, as indicated by the dotted line in the figure. The ionisation peak can also cause a shoulder in the temperature profile. Obviously, this is only the case when the temperature exceeds the ionisation temperature.

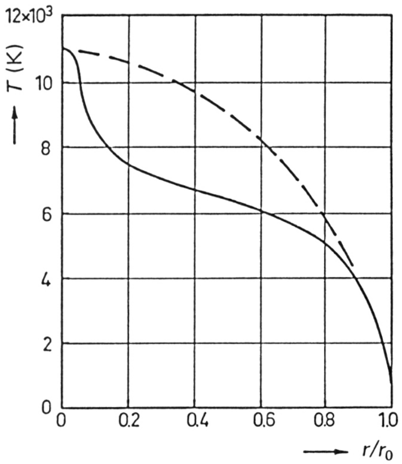

Figure 1.17. Arc temperature T as a function of the relative distance r/r_0 from the axis of the arc for nitrogen (continuous line) and for a mono-atomic gas (dotted line).

1.3.5 Radiation

In addition to heat conduction the arc column also looses heat by radiation. The radiation is emitted over a wide wavelength range, including the visual spectrum and generally consists of a line spectrum superimposed on a background continuum. At low temperatures, the line spectrum dominates, while with increasing temperature the line spectrum gradually changes into continuous radiation. As an example Figure 1.18 shows the spectrum of a 200 A arc in argon.

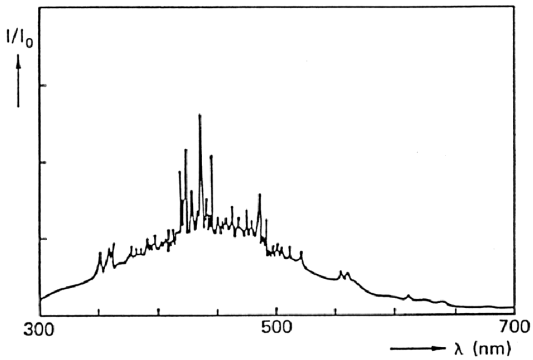

Figure 1.18. Relative radiation intensity I/I_0 as a function of wavelength λ of a 200 A arc in argon.

Calculation of the heat lost by radiation is very complicated. At sufficiently high temperature, however, the line spectrum may be neglected with respect to the continuum, and the arc column may be considered a 'black body'. In that case, the total energy lost by radiation per unit time and unit area, is given by the Stefan-Boltzmann law:

$$S(T) = cT^4 \tag{1.16}$$

where c is a constant equal to 5.67×10^{-8} $Wm^{-2}K^{-4}$. Obviously, radiation plays an important role in the heat balance of the arc column, especially at high temperature. In the case of a welding arc, for instance, the heat lost by radiation may be as large as 20 to 30% of the total heat lost by the arc column.

1.3.6 Plasma flow

Plasma flow is a phenomenon, which plays an important role in the arc column. Due to its convective nature it influences the temperature distribution of the arc column and thus affects its energy balance.

Plasma flow in the arc column may be generated in different ways. Firstly, flow is generated as a result of local temperature differences and corresponding differences in gas density. Usually, this thermally induced (buoyancy) flow is dominated by another type of flow, which is generated by electromagnetic forces and is often referred to as the plasma jet. This plasma jet is directed axially and originates from the most contracted part of the arc column (in the case of arc welding close to the electrode). Inside the plasma jet, flow velocities of over 200 ms^{-1} have been observed. (For comparison: a wind velocity 7 on the scale of Beaufort corresponds with 15.5 ms^{-1}.) As an illustration, Figure 1.19 shows the flow pattern of a 200 A arc in air. It can be seen that the flow velocity has its maximum value near the electrode and decreases rapidly in radial direction and with the distance to the electrode.

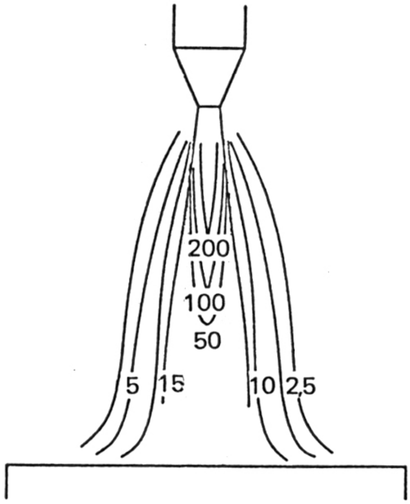

Figure 1.19. Plasma flow in a 200 A arc in air. The lines indicate equal flow velocity (ms^{-1}).

The existence of the plasma jet can be explained in terms of electromagnetic Lorentz forces operating in the arc column. This can be qualitatively understood by considering the total electric current passing through the arc as being composed of small elementary currents. These elementary currents attract each other according to Lorentz law, which results in an increase of pressure. As the attracting force between the elementary currents is inversely proportional to the distance between them, the pressure increase will be largest in the most contracted part of the arc and decreases with increasing arc diameter. It is evident that the pressure gradient created in this way, results in plasma flow.

1.4 The cathode fall zone

The cathode fall zone is an extremely thin layer (~ 10^{-8} m), connecting the relatively cold cathode and the relatively hot arc column.
The zone is characterized by a positive space charge (a surplus of positive ions), combined with a drop in voltage (see equation (1.1) and Figure 1.5). The value of the

voltage drop lies between 10 and 20 V, the electric field strength in this zone therefore has a value of about 10^9 Vm^{-1}. Another important property of the cathode fall zone is the absence of thermal equilibrium: because of the relatively small number of collisions in this zone between the cold electrons, originating from the cathode, and the hot heavy particles (atoms, ions), originating from the arc column, the exchange of energy between these particles is incomplete, which implies that:

$$T_e \ll T_g \tag{1.17}$$

The primary function of the cathode is the emission of electrons. These electrons, once emitted, will travel towards the anode under the influence of the electric field.
Electrons can be emitted from the cathode by heating the cathode to a sufficiently high temperature. This mechanism, usually referred to as thermionic emission, is only possible when using high-melting point cathode materials like tungsten and generally requires a high arc current. The current density of the emitted electrons j_e in the case of thermionic emission is given by the Richardson-Dushman equation:

$$j_e = AT^2 \exp\left(-\frac{e\varphi}{kT}\right) \tag{1.18}$$

where A represents a material constant (which for metals has a value around 1.2×10^6 $Am^{-2}K^{-2}$), T the temperature, k the Boltzmann constant, e the charge of the electron and φ the threshold potential for electron emission of the cathode. The factor $e\varphi$ equals the energy required to remove an electron from the cathode material and is usually referred to as the work function. In Table 1.3 the work function of a number of metals is listed.
Table 1.3 shows that the work function of metals lies around 4 to 5 eV. The work function of oxides is generally considerably lower (~ 2 eV). This is why small quantities of specific oxides (zirconium oxide, cerium oxide, lanthanum oxide) are often added to the cathode to enhance the electron emission.

Table 1.3. Work function of a number of metals.

Metal	Work function (eV)
Al	4.0
Cu	4.3
Fe	4.4
Ni	5.0
W	4.6

When the cathode temperature is insufficiently high, as in the case of low-melting

point metals such as steel and in the case of low arc current, the necessary electrons to sustain the arc cannot be provided by thermionic emission alone. Under these conditions, field emission begins to play a role. Field emission is a process, whereby electrons tunnel through a potential barrier in the presence of a high electric field. The theoretical background of this process is extremely complex and will not be discussed here. It must be noted, however, that field emission requires not only a high electric field but also a high current density (> 10^{10} Am^{-2}). Such a high current density can only be achieved by contraction of the arc. Due to this contraction the contact area between the arc and the cathode narrows to a so-called cathode spot. These spots are generally highly unstable and move at high speeds across the surface of the cathode. They have a strong preference for those places at the surface where oxides are present. Although a conclusive explanation for this phenomenon is not yet available, it is evident that oxides play an essential role in reaching the necessary high electric field strength.
In the direct vicinity of the cathode the current is entirely carried by electrons, whereas in the arc column also positive ions contribute to the current. To obey the requirement of current continuity ion-electron recombination takes place in the cathode fall region.

1.5 The anode fall zone

The anode fall zone is a very thin layer (10^{-7} m), forming the transition between the relatively cool anode and the relatively hot arc column. This zone is characterized by the presence of a negative space charge (a lack of positive ions), combined with a drop in voltage (see equation (1.1) and Figure 1.5). The value of the voltage drop lies between 1 and 10 V.
Similar to the case of the cathode fall region no thermal equilibrium exists in the anode fall region: due to the small number of collisions in this zone between the hot electrons, originating from the arc column, and the cold heavy particles, present in the vicinity of the anode, the exchange of energy between these particles is incomplete, which implies that:

$$T_e \gg T_g \tag{1.19}$$

At low arc current (< 40 A), arc contraction may occur in front of the anode, resulting in an anode spot. Anode spots are generally more stable than cathode spots, but under specific circumstances they may cause unstable arc behaviour.
While the current in the arc column is carried for the major part by electrons and for a small part by positive ions (see equation (1.13)), the current just before the anode is a pure electron current, because the anode is not able to produce positive ions. To overcome this apparent current discontinuity ionisation must occur in the anode fall

zone. The produced ions move to the arc column, while the produced electrons move to the anode.

1.6 Arc ignition

Different methods exist to ignite an arc. The essential step in all these methods is to create the conditions, which make it possible for the cathode to emit electrons. The three most important methods of ignition are briefly discussed below.

1.6.1 Ignition by electric breakdown

Consider two electrodes positioned at a distance d from each other in a gas at pressure p, with an electric voltage V between the electrodes. When no charged particles are present between the electrodes, the gas will remain non-conductive. In reality however, this situation does not occur: there will always be electrons present in the region between the electrodes, as a result of cosmic radiation or the photo-electric effect. Each electron will then, under the influence of the electric field $E = V/d$, move towards the anode. While moving, it will collide with neutral gas atoms or molecules. Between two consecutive collisions, the electron will absorb an average energy eEl, where e is the electric charge of the electron and l is the electron free path length. If this energy is equal to or greater than the ionisation energy E_i of the gas, the electron will be able to ionise a gas atom, producing an extra electron and a positive ion. This process can now continue as a chain reaction and cause an avalanche of electrons and positive ions. The number of electrons dn, formed per volt, is proportional to the number of electrons present, or:

$$\frac{dn}{dV} = \alpha n \tag{1.20}$$

where the avalanche factor α represents the number of ionisations per electron per volt. The solution of differential equation (1.20) can be written as:

$$n = e^{\alpha V} \tag{1.21}$$

The quantity $e^{\alpha V}$ is the number of electrons per avalanche, while the number of positive ions per avalanche equals $e^{\alpha V} - 1$. These ions move towards the cathode, are neutralised there and release secondary electrons from the cathode, which in turn can start new avalanches. If γ is the probability that an electron is released from the cathode by an ion, then $\gamma(e^{\alpha V} - 1)$ secondary electrons will be produced. It is evident that electric breakdown (the exponential increase of current) will occur when:

$$\gamma(e^{\alpha V} - 1) \geq 1 \tag{1.22}$$

Neglecting the value 1 with respect to $e^{\alpha V}$, the breakdown voltage V_B can be written as:

$$V_B = -\frac{1}{\alpha}\ln\gamma \qquad (1.23)$$

The avalanche factor α depends on the type of gas and on *E/p*. Both α and V_B can therefore be expressed as a function of *pd* (Paschen law). In Figure 1.20 V_B is plotted as a function of *pd* for air and argon.

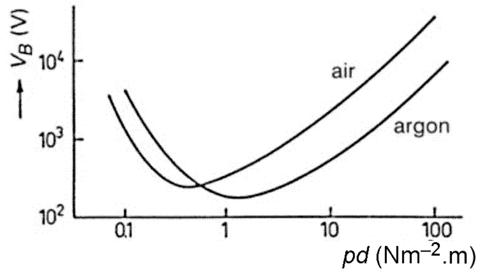

Figure 1.20. Paschen-curves for air and argon.

It can be seen that the curves have a minimum for a certain value of *pd*. The occurrence of this minimum can be understood by realising that α must be relatively small and therefore V_B relatively large when:

- the pressure is small (the number of electron-atom collisions is small);
- the pressure is large (the elastic energy loss of the electrons is large).

When the voltage between the electrodes exceeds V_B breakdown takes place, which via Townsend discharge and glow discharge will result in arc ignition.
Breakdown ignition requires a specific power source: on the one hand, a high voltage is required (a voltage exceeding V_B), on the other hand, immediately after ignition a constant high current must be supplied at low voltage. These demands can be met by superimposing a voltage peak on the welding voltage. When using direct current one initial peak is sufficient, when using alternating current, a peak frequency of 100 Hz (alternating between positive and negative) is necessary for ignition and maintenance of the arc.

1.6.2 Ignition by direct heating of the cathode

Another way of igniting the arc is local heating of the cathode. In this case, the electrons necessary for the initial phase of ignition will be produced by thermionic emission of the cathode. The emitted electrons will be accelerated under the influence of the electric field, resulting in the ionisation of neutral atoms or molecules, thus creating a stable arc.

A practical way of local cathode heating is bringing the cathode in contact with the anode and maintaining this contact for a brief period. During this short-circuiting period, a high current will pass through the contact area between the electrodes. This will result in melting and the formation of a bridge of liquid metal. When separating the electrode(s), the liquid bridge will contract, concentrating the Joule heating in an increasingly smaller region. Finally, contact is broken, resulting in a cathode (and anode) of very high temperature.
A disadvantage of short-circuit arc ignition is that contamination of (and possible damage to) the electrodes may occur. However, this method can be used without problems in the case of arc welding with a consumable electrode.

1.6.3 High-frequency ignition

This method involves the superposition of a high-frequency voltage (several MHz, several kV) on the arc voltage. Because of the presence of this high frequency field, electrons present between the electrodes will start to oscillate without reaching the electrodes. This will result in the production of a large number of electrons and positive ions. Under the influence of the electric field, the electrons will be transported to the anode, while the positive ions move to the cathode. Due to the impact of the positive ions the cathode will be heated, resulting in thermionic emission and the creation of a stationary arc.

1.7 The arc welding process

An important industrial application of the arc is its use as heat source in arc welding. The principle of arc welding is shown schematically in Figure 1.21. Between a metal electrode, which can be either consumable (as in Figure 1.21) or non-consumable, and the workpiece to be welded, an electric arc (the welding arc) is ignited. The distance between the electrode and the workpiece is usually between 0.1 and 1 cm. The electric current is supplied by a transformer (when welding with alternating current) or a rectifier (when welding with direct current).

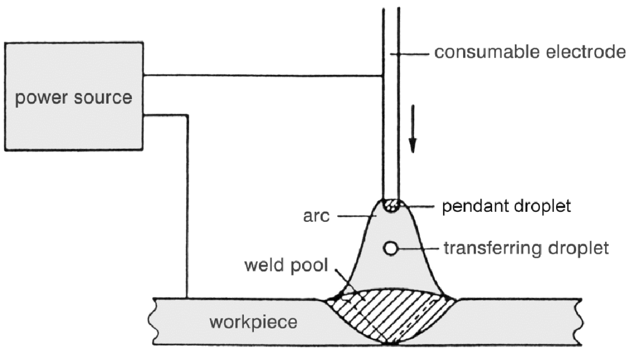

Figure 1.21. Principle of arc welding.

The workpiece is heated by the electric energy generated by the welding arc, which results in local melting and the formation of a weld pool. In the case of a consumable electrode, molten electrode material will also enter the weld pool in the form of droplets. By moving the electrode along the welding groove (and in the case of a consumable electrode also downward, to compensate for the melting of the electrode), the welding groove is filled with molten metal. The liquid metal will then cool and solidify, thus creating the desired welded joint.
Arc welding has a wide range of applications. Consequently, a large variety of weld configurations, groove geometries and welding positions can be distinguished. The most common of these are shown schematically in Appendix A, B and C.

Generally, a distinction should be made between single-pass welds and multi-pass welds, a weld pass having typically a thickness of 3 to 4 mm. As an illustration the transverse cross-sections of a single-pass weld and a multi-pass weld are schematically shown in Figure 1.22.

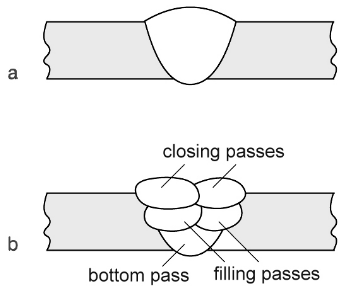

Figure 1.22. Schematic representation of the transverse cross-section of a) a single-pass weld and b) a multi-pass weld.

During multi-pass welding the deposition of a pass results in local heating of the preceding pass, thus affecting its properties (heat treatment). The magnitude of this effect depends strongly on the inter-pass temperature.

For the practical application of arc welding a number of process variants is available, the most important being:

- Gas tungsten arc welding;
- Plasma arc welding;
- Shielded metal arc welding;
- Gas metal arc welding;
- Submerged arc welding.

These process variants will be briefly discussed in the following sections.

1.7.1 Gas tungsten arc welding

The principle of gas tungsten arc (GTA) welding, sometimes also referred to as tungsten inert gas (TIG) welding, is schematically depicted in Figure 1.23.
In GTA welding a non-consumable tungsten electrode is used. Usually, small quantities of oxides are added to the tungsten to lower the work function with the aim to increase the electron emission. This provides a more stable arc, facilitates arc ignition and decreases electrode erosion. To shield the electrode and the liquid metal from the ambient air, an inert shielding gas is used (usually argon, sometimes helium or an argon-helium mixture). The shielding gas is directed around the electrode and the liquid metal by a nozzle, placed concentrically around the electrode. If required, consumable material in the form of a wire or a rod can be added manually or automatically.
In the case of GTA welding, contact between the electrode and the workpiece must be avoided in order to prevent contamination of both the electrode and the weld pool. For this reason high voltage pulses are used to (re)ignite the arc.

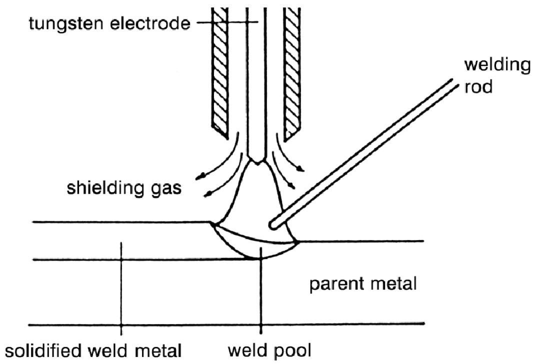

Figure 1.23. Gas tungsten arc welding.

GTA welding is possible for all metals. The process is most suitable for welding thin metal plate (sheet) and metal parts with small dimensions (precision work). GTA welding is also often used for depositing the root pass in a multiple-pass weld.
In GTA welding, direct current is normally used (electrode negative polarity; electrode positive polarity would overheat the electrode – see Section 1.8). When welding aluminium with pure argon as shielding gas, alternating current must be used because of the presence of the impenetrable aluminiumoxide skin covering the liquid metal; when helium or a helium-rich argon-helium mixture is used as shielding gas, normal GTA welding (direct current, electrode negative) is possible. Sometimes pulsed (direct) current is used, with a frequency of 1-10 Hz. Pulsed current arc welding results in a stabilized arc and a deeper penetration of the weld.
Both the shape of the arc and the shape of the weld pool are strongly affected by the top angle of the electrode. Generally, a smaller top angle results in a wider arc and a

wider and shallower weld pool. This is illustrated in Figure 1.24.

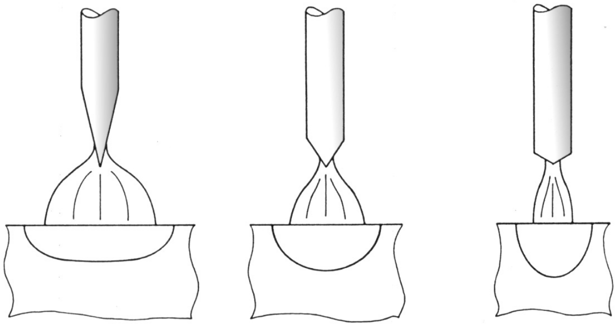

Figure 1.24. The influence of the electrode tip angle on the shape of the arc and the weld pool.

1.7.2 Plasma arc welding

Plasma arc welding (Figure 1.25) can be considered as a refinement of GTA welding. The electrode material consists of tungsten (with dispersed oxides) and an inert shielding gas (argon, helium or an argon-helium mixture) is used. In plasma welding, however, the arc is constricted at the electrode side by a water-cooled nozzle. This creates a plasma jet with a very high energy density. To protect the plasma and the weld pool from atmospheric interference, an additional gas flow is used (argon, helium, argon-helium or argon-hydrogen). Because of the high temperature of the plasma jet (up to 25000 K), materials with very high melting points can be melted and welded.

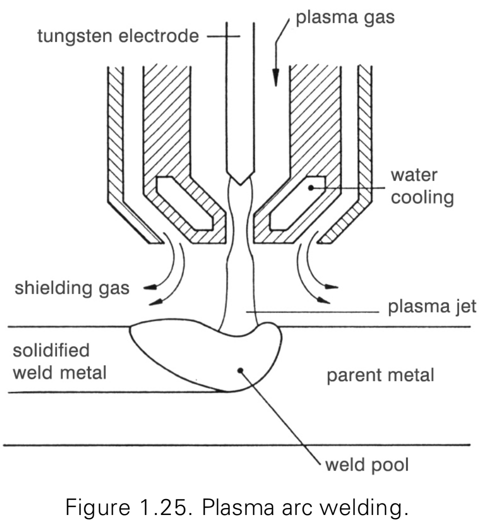

Figure 1.25. Plasma arc welding.

A special technique that can be applied in plasma welding is the keyhole technique.

This technique makes it possible to produce fully penetrated welds in thick plates, see Figure 1.26. The plasma jet melts a hole in the plates, which are placed closely against each other. Moving along the interface of the plates, this hole remains stable because of the surface tension of the liquid metal and the vapour pressure (the metal flows around the hole from front to back). This procedure can be compared to pulling a hot wire through a block of ice.

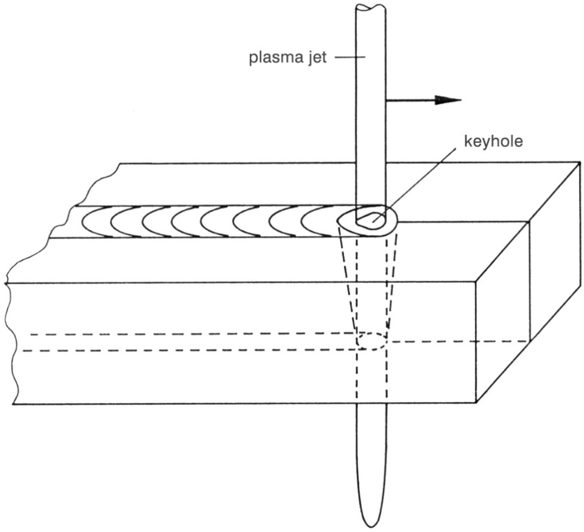

Figure 1.26. The keyhole technique.

In the situation described here, the arc current flows from the electrode to the workpiece and the arc is referred to as a transferring arc. It is also possible to maintain an arc between the electrode and the nozzle. This creates a 'free' plasma jet, which is referred to as a non-transferring arc. An advantage of the non-transferring arc is the possibility to weld or melt electrically non-conductive materials.

1.7.3 Shielded metal arc welding

In shielded metal arc (SMA) welding a consumable electrode is used (see Figure 1.27). This electrode consists of a metal rod (length 350 or 450 mm, diameter between 1.6 and 7 mm), which is covered by a coating. The coating contains different powdered materials, each with its own specific function. The most important functions of the coating are:

- directing the arc and the droplets towards the weld pool (by the formation of a cup-like geometry at the tip of the electrode);
- providing a protective gas (e.g. CO_2 from carbonates);
- producing a slag to protect the liquid metal;
- stabilizing the arc;

- alloying the weld metal;
- increasing the melting efficiency (by adding metal powder).

Additional gas protection is not necessary in shielded metal arc welding, because protection of the liquid metal is already provided by gas and slag originating from the coating.

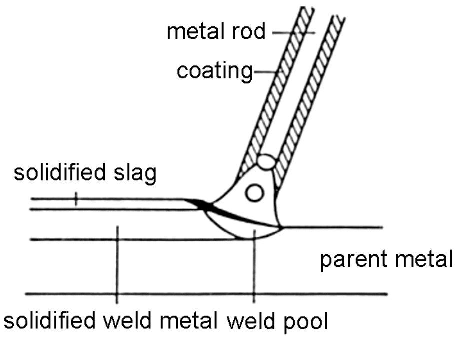

Figure 1.27. Shielded metal arc welding.

A problem in SMA welding is that, in spite of the protective measures, relatively large quantities of hydrogen can be absorbed by the liquid weld metal. The origin of this hydrogen is water, which is present in the hygroscopic electrode coating and which will be released in the arc when welding. Keeping the electrodes dry, or drying them before use, is therefore a necessity. Depending on the electrode type, alternating current or direct current (electrode positive or electrode negative) is used in SMA welding.

SMA welding is the oldest variant of the arc welding process and is still widely utilised for welding steel and to a lesser extend for welding nickel and copper alloys. It is a flexible process and a wide range of electrodes exists for different alloys, material thicknesses and welding positions. A disadvantage is that the process can hardly be mechanised or automated.

1.7.4 Gas metal arc welding

The principle of gas metal arc (GMA) welding is shown in Figure 1.28. In this process (sometimes also referred to as metal inert gas (MIG) or metal active gas (MAG) welding) a consumable electrode is used in the form of a continuously fed wire. The wire can be either solid metal, or may consist of a thin metal tube filled with powder (flux-cored wire).

A few examples of flux-cored wires are shown in Figure 1.29. Use of flux-cored wire has the advantage that the chemical composition of the weld metal can easily be adapted via the powder filling. The current is transferred to the electrode at the contact tube. The part of the wire, which carries the current (stick-out length) is therefore short, allowing for high currents, even when using wire of small diameter (e.g. up to 300 A with a 1.2 mm diameter wire). Normally direct current (electrode positive) is used. This is directly related to the way the droplet transport takes place (see Section 1.9).

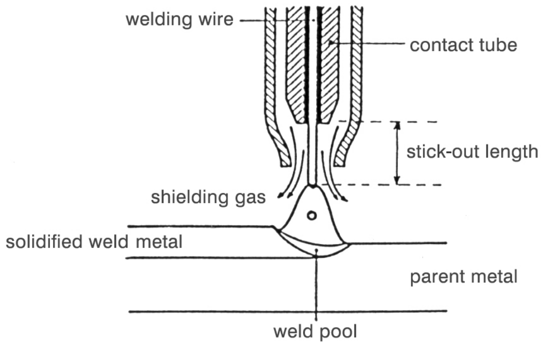

Figure 1.28. Gas metal arc welding.

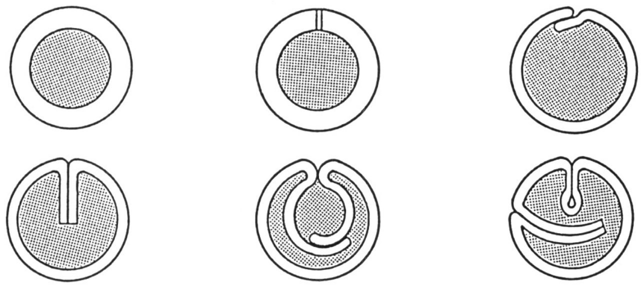

Figure 1.29. Examples of flux-cored wires in cross-section.

In GMA welding different shielding gases may be employed, depending on the metal to be welded. Usually an inert gas (argon, helium or an argon-helium mixture) is used when welding non-ferrous metals, while in the case of welding steel an inert gas is employed, to which small amounts of oxygen and/or CO_2 are added. These oxidising additions stabilise the arc and improve the flow characteristics of the liquid weld metal. A special type of GMA welding is CO_2 welding, where pure CO_2 is used as the shielding gas. Table 1.4 lists the most commonly used shielding gases.
GMA welding without an externally supplied shielding gas is also possible. However, this requires the use of a so-called self-shielding wire. This is a flux-cored wire, containing chemicals which decompose at high temperature, releasing shielding gas(ses), such as CO_2.

In GMA welding, a distinction must be made between open-arc welding and short-circuit arc welding. In the case of open-arc welding, the arc burns continuously, and no short-circuiting occurs between the electrode and the workpiece. In this situation metal transport takes place in the form of distinct droplets transferring through the arc towards the weld pool, see Section 1.9. In the case of short-circuit arc welding, periodic short-circuiting occurs between the electrode and the workpiece. Material transport takes place during the short-circuiting period, while the arc is extinguished. Short-circuit arc welding is operated at relatively low values of voltage and current. Figure 1.30 shows schematically the voltage and current during short-circuit arc welding. Because of the relatively small heat input the short-circuit arc welding process is particularly suited for welding thin (sheet) materials and for welding in position. Application of short-circuit arc welding is limited by the risk of lack of fusion due to the low heat input (see Section 3.7) and by the occurrence of spattering.

Table 1.4. Shielding gases used in GMA welding.

shielding gas	material	remarks
Ar	non-ferrous metals	stable arc
He	non-ferrous metals	hot and less stable arc; suitable for thick materials
Ar + 1 - 2% O_2	heat resistant and stainless steels	good fluidity of weld metal
Ar + 2 - 3% CO_2	heat resistant and stainless steels	more viscous weld metal
Ar + 5 - 20% CO_2	unalloyed and low-alloy steels	relatively stable arc; the more CO_2, the deeper the penetration
CO_2	unalloyed and low-alloy steels	instable arc; spattering

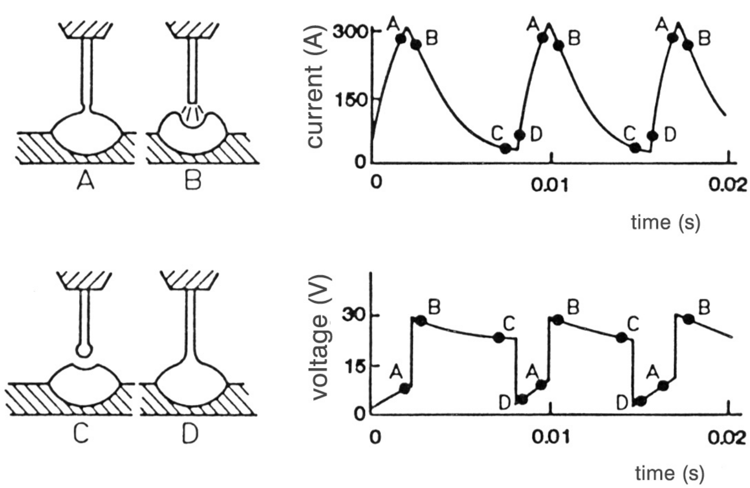

Figure 1.30. Voltage and current as a function of time in short-circuit arc welding.

GMA welding has a wide application range, expanding at the cost of shielded metal arc welding. An important advantage is the possibility to mechanise or automate the process.

1.7.5 Submerged arc welding

In submerged arc (SA) welding a consumable electrode is used in the form of a wire (solid or flux-cored) or a strip, see Figure 1.31. The arc is entirely surrounded by a powder (flux), which has a similar function as that of the coating of the electrode used in shielded metal arc welding and forms a slag. An advantage of this process is the possibility to use very high currents. A disadvantage is that it can only be applied for welding in flat position.

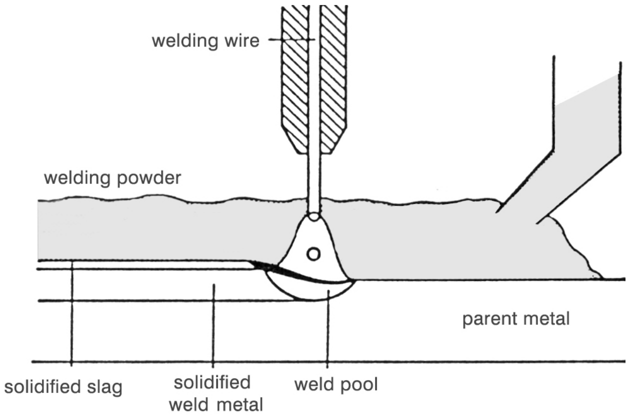

Figure 1.31. Submerged arc welding.

Submerged arc welding is mainly used for welding thick plates and pipes, and for the application of metal clad layers (cladding).
Both alternating current and direct current (electrode positive or electrode negative) can be used.

1.8 Heat transfer in arc welding

One of the most important characteristics of the arc is its non-linear voltage distribution (see Section 1.2). This causes a disproportionally large fraction of the total arc energy generated in the arc to be transferred to the cathode and the anode. It is particularly this characteristic that makes the arc suitable as a heat source in welding.
The amount of heat transferred per unit time to the cathode (Q_c) and to the anode (Q_a) can be calculated using the energy balance. For the cathode and its immediate surroundings (cathode fall zone), this leads to the following equation:

$$Q_c = V_c I + c_c V_{col} I - \varphi_c I - \frac{3}{2}\frac{k(T_{col} - T_c)}{e} I \qquad (1.24)$$

The term V_cI represents the energy produced in the cathode fall zone; $c_cV_{col}I$ is the fraction of the energy produced in the arc column that is transferred to the cathode by heat conduction, convection and radiation; φ_cI is the energy required to emit the electrons from the cathode; the term $\frac{3}{2}k(T_{col} - T_c)I/e$ is the energy required to raise the temperature of the electrons from the cathode temperature T_c to the arc column temperature T_{col}.

In a similar way the following equation can be derived for the anode and its immediate surroundings (anode fall zone):

$$Q_a = V_a I + c_a V_{col} I + \varphi_a I + \frac{3}{2}\frac{k(T_{col} - T_a)}{e} I \qquad (1.25)$$

in which the different terms correspond to those used in equation (1.24).

It should be noted that, whereas the two last terms of equation (1.24) are negative (both terms represent energy losses)¸ the corresponding terms of equation (1.25) are positive (both terms contribute to the energy transferred to the anode).

Equations (1.24) and (1.25) show that both Q_c en Q_a are proportional to the current and that $Q_a > Q_c$ (more heat is released to the anode than to the cathode). However, the situation where $Q_a < Q_c$ may also occur. This is the case when V_c is relatively large and/or V_a is relatively small and, more specifically, when $V_c - V_a > 10$ V.

An important quantity in arc welding is the process efficiency η_p. This is the fraction of the total arc energy that is transferred to the workpiece (either directly or via the consumable electrode). For the different variants of the arc welding process the following process efficiencies can be defined:

– for welding with a non-consumable electrode (direct current, electrode positive):

$$\eta_p = \frac{Q_c}{VI} \times 100\% \qquad (1.26)$$

– for welding with a non-consumable electrode (direct current, electrode negative):

$$\eta_p = \frac{Q_a}{VI} \times 100\% \qquad (1.27)$$

– for welding with a non-consumable electrode (alternating current):

$$\eta_p = \frac{Q_c + Q_a}{2VI} \times 100\% \qquad (1.28)$$

– for welding with a consumable electrode (direct current and alternating current):

$$\eta_\mathrm{p} = \frac{Q_c + Q_a}{VI} \times 100\% \tag{1.29}$$

Table 1.5 shows typical values of η_p for different variants of the arc welding process.

Table 1.5. Process efficiency η_p for different variants of the arc welding process.

Arc welding process	η_p (%)
GTA welding (electrode negative)	50–80
GTA welding (electrode positive)	40–70
Plasma arc welding	50–80
SMA welding	70–90
GMA welding	60–90
SA welding	90–100

The melting efficiency η_m is the fraction of the total arc energy, which is required to heat and melt the metal. The melting efficiency can be estimated using the following equation:

$$\eta_\mathrm{m} = \frac{qAv}{VI} \tag{1.30}$$

where q represents the amount of energy necessary to heat and melt a unit volume of the metal, A is the surface area of the transverse cross-section of the weld, and v is the travel speed (the speed of the welding arc relative to the workpiece).
The melting efficiency increases with the energy density of the arc, because the higher the energy density, the faster the metal is heated and the less heat will be lost by heat conduction. Table 1.6 shows melting efficiencies and energy densities of some welding processes.

Another important quantity in arc welding is the heat input. The heat input determines the peak temperature and the cooling rate in and around the weld, and in this way influences the structure and properties of the welded joint (see Section 3.1).
The heat input W is defined as the amount of heat transferred to the workpiece per unit length of the weld, and can be written as:

$$W = \frac{\eta_p VI}{v} \tag{1.31}$$

Table 1.6. Melting efficiency η_m and energy density of some welding processes.

Welding process	η_m (%)	Energy density (MW/m^2)
Oxyfual gas welding	2 – 10	10 – 10^2
GTA welding	20 – 40	10^2 – 10^3
Plasma arc welding	40 – 60	10^3 – 10^4
Laser welding	90 – 100	10^4 – 10^5
Electron beam welding	90 – 100	10^6 – 10^7

It must be noted that in this section Joule heating of the cathode and the anode is not taken into account. This effect will be dealt with when discussing the melting rate (see Section 1.10).

1.9 Metal transport in arc welding

In the case of arc welding with a consumable electrode (coated electrode, solid wire, flux-cored wire) not only the workpiece, but also the electrode tip will melt. As a result, a droplet will form at the tip of the electrode. When sufficiently large, this droplet will be detached from the electrode tip and transported to the weld pool under the influence of the following forces:

– *Gravity*

Gravity will promote or oppose the detachment of the droplet, depending on the geometric direction of the electrode.

The gravitational force can be expressed as:

$$F_g = \frac{4}{3}\pi\ r_d^3\ \rho\ g \tag{1.32}$$

with r_d the droplet radius, ρ the droplet density and g the gravitational acceleration.

– *Surface tension*

Surface tension will always oppose droplet detachment, as it strives to minimise the surface energy. The surface tension force can be written as:

$$F_s = 2\pi\ r_e\ \gamma \tag{1.33}$$

with r_e the radius of the electrode and γ the surface tension of the liquid metal.

– *Plasma drag force*

As shown in Section 1.3, a plasma flow is generated in the welding arc. This plasma flow has a dragging effect on the droplet, which promotes droplet detachment. The plasma drag force can be approximated by the equation:

$$F_d = \frac{1}{2} c_d A \rho_p v_p^2 \tag{1.34}$$

with c_d the drag coefficient, A the cross-section surface area of the droplet, ρ_p the density of the plasma and v_p the velocity of the plasma.

– *Lorentz force*
Due to the distribution of the current within the droplet, an electromagnetic (Lorentz) force will act on it. This force has the same origin as the force generating the plasma jet (see Section 1.3.6) and can be expressed as:

$$F_l = C \frac{\mu_0}{4\pi} I^2 \tag{1.35}$$

with μ_0 the permeability of free space and C a factor, determined by the current distribution within the droplet. In the case of current divergence in the droplet (the contact area between the arc and the droplet is larger than the electrode diameter), C is positive and droplet detachment is promoted. In the case of current convergence in the droplet (the contact area between the arc and the droplet is smaller than the electrode diameter), C is negative and droplet detachment will be opposed. The situation is shown schematically in Figure 1.32.

– *Explosive forces*
Explosive forces are the result of gas development inside the droplet, which may lead to detachment of liquid metal particles in all directions. An example of gas development in liquid weld metal is the formation of CO in unalloyed steel, as a result of oxygen absorption.

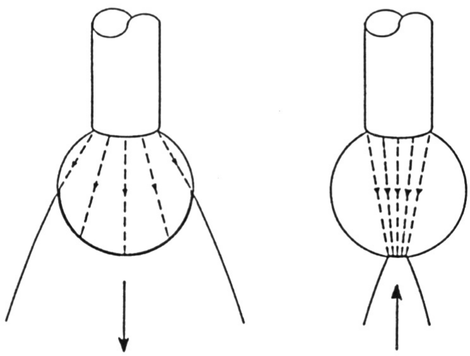

Figure 1.32. Lorentz force acting on a metal droplet. Left: current divergence; right: current convergence.

It is evident that the magnitude and the direction of the forces mentioned above strongly depend on the welding conditions. Combined, they determine the size and shape of the droplets and the frequency and regularity of the droplet transfer.
Research shows that different types of droplet transfer can be distinguished. These types have been classified by the International Institute of Welding (IIW) and are shown in Table 1.7 and Figure 1.33. In the next section further attention will be given to the metal transport in GMA welding, SMA welding and SA welding.

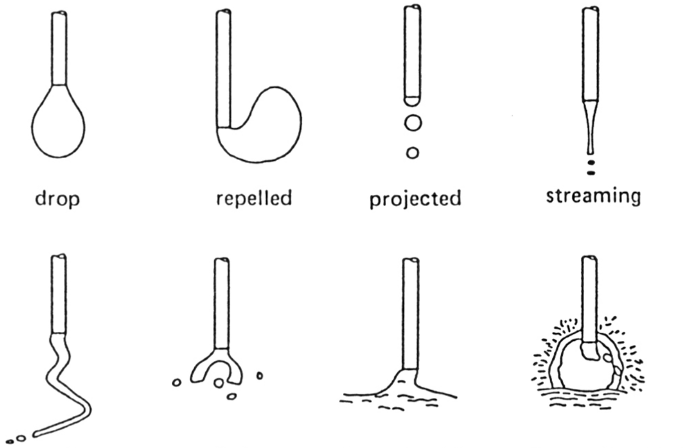

Figure 1.33. The different types of droplet transfer, according to the classification of the International Institute of Welding (IIW).

Table 1.7. IIW-classification of metal transfer.

Designation of transfer type	Welding process
1. Free flight transfer	
1.1. Globular	
1.1.1. Drop	Low-current GMA welding
1.1.2. Repelled	CO_2-shielded GMA welding
1.2. Spray	
1.2.1. Projected	intermediate-current GMA welding
1.2.2. Streaming	Medium-current GMA welding
1.2.3. Rotating	High-current GMA welding
1.3. Explosive	SMA welding
2. Bridging transfer	
2.1. Short-circuiting	Short-circuit GMA welding, SMA welding
2.2. Bridging without interruption	Welding with flux-cored wire
3. Slag-protected transfer	
3.1. Flux-wall guided	Submerged arc welding
3.2. Other modes	SMA welding, flux-cored wire welding, electroslag welding

GMA welding

Metal transport in GMA welding depends strongly on the shielding gas, the polarity and the current.
When welding in an argon-rich shielding gas with electrode positive polarity and a relatively low current, metal transport takes place in the form of large droplets with a diameter several times larger than the electrode diameter, at a frequency of several droplets per second (drop transfer). When the current is increased above a certain value (the critical current I_{cr}), an abrupt change in metal transport takes place. Above the critical current, the droplets are transferred in the form of a regular stream of droplets with a diameter roughly the same as the electrode diameter, at a frequency of several hundreds droplets per second (projected transfer).
The critical current I_{cr} depends on the electrode material and the diameter of the electrode, and has a value of approximately 275 A for 1.6 mm steel wire (see Figure 1.34).

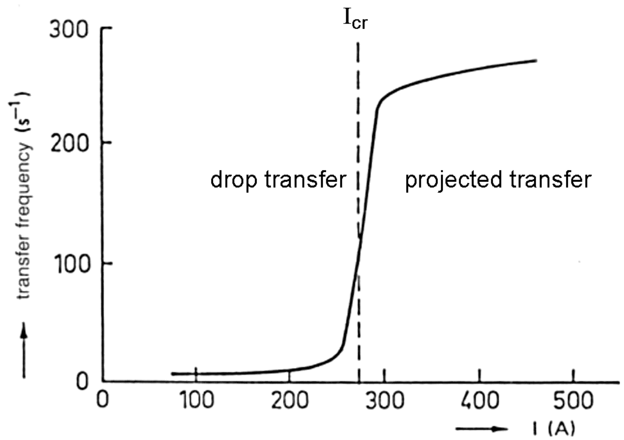

Figure 1.34. Droplet transfer frequency as a function of current in the case of GMA welding in argon with a 1.6 mm steel wire as the electrode.

When the current is further increased, the metal transport changes to a spray of very fine droplets (streaming transfer). At still higher current, the metal transport develops into a spiral of liquid metal (rotating transfer). Figure 1.35 shows schematically under which conditions (arc voltage, arc current) the three main forms of metal transport occur. The three regions in this graph are often referred to as 'GMA operating regions'.

To achieve metal transport in the spray transfer mode at relatively low current (below the critical current value), use can be made of current pulses (see Figure 1.36). During the pulse time the current exceeds the critical current and droplet transfer will take place in the projected mode. The frequency and pulse duration are usually chosen in such a way, that one droplet is detached per pulse.

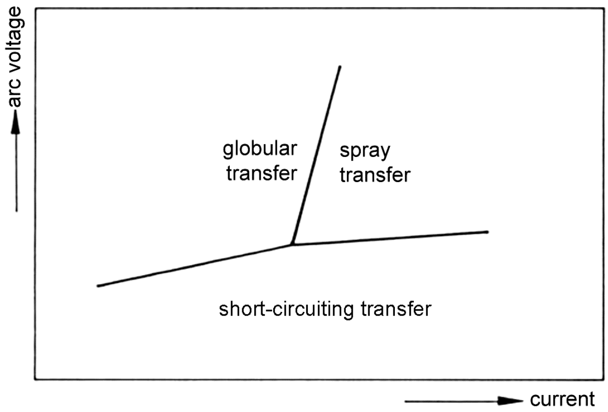

Figure 1.35. GMA operating regions.

In the case of GMA welding in an argon-rich shielding gas with negative electrode polarity, the arc is unstable under all conditions, while droplet transfer is very irregular with large droplets and much spattering (repelled transfer). This behaviour is caused by the current convergence in the droplet as a result of the small contact area between the arc and the droplet (cathode spot). Because of this current convergence, a Lorentz force acts on the droplet, the direction of which depends on the location of the cathode spot (see Figure 1.32). It is evident that this Lorentz force opposes droplet detachment and induces spattering.

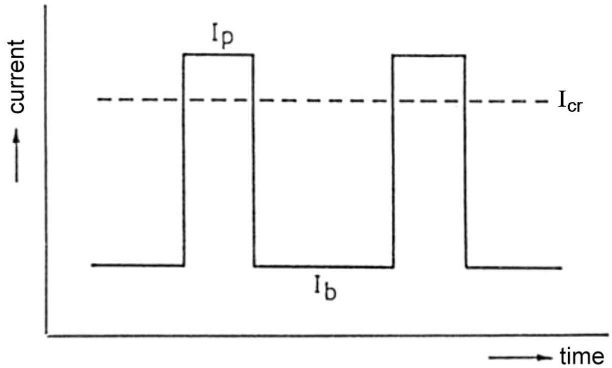

Figure 1.36. The principle of pulsed current GMA welding.

Some improvements in metal transport can be achieved by adding small amounts of oxygen to the shielding gas, or applying an alkali-containing coating on the electrode surface. These improvements are a direct result of the enlargement of the cathode spot resulting in a reduction of the counteracting Lorentz force.

The behaviour described in the foregoing, is specific for situations where argon-rich shielding gases are used. When using helium, globular transfer occurs under all conditions: drop transfer when welding with positive electrode polarity, repelled transfer when welding with negative electrode polarity. Despite the negative effect on metal transfer, helium or helium-argon mixtures are still used in some cases, because the use of helium results in a better weld shape (see Figure 1.37).

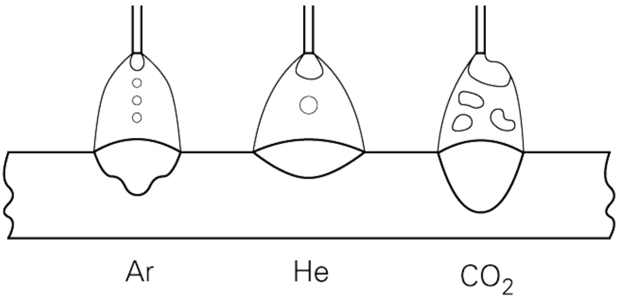

Figure 1.37. GMA weld cross-sections for different shielding gases.

When CO_2 is used as shielding gas, instable metal transport occurs both with positive and with negative electrode polarity, resulting in large droplets and considerable spattering (repelled transfer). Improvement of metal transport is achieved by applying a thin alkali-containing coating on the electrode. Using positive electrode polarity usually gives the best results.
During short-circuit GMA welding, both in argon and in helium, metal transport occurs in the short-circuiting transfer mode (see Figure 1.30). In this case, the liquid metal is transported from the electrode to the weld pool during the short-circuits (hundreds per second). Spattering can be reduced by limiting the rate of the current increase during the short-circuit phase.

SMA welding

Metal transport in shielded metal arc welding is a very complex phenomenon. It appears that different modes of droplet transfer can occur, separately or in combination. Which droplet transfer mode dominates in a certain situation, depends on the chemical composition of the coating, the polarity and the current level.

SA welding

In submerged arc welding also different types of metal transfer can occur. However, high-speed X-ray images, made during welding, show that flux-wall guided transfer is the dominant transfer mode. Hereby, droplets of liquid metal are transported from the tip of the electrode to the weld pool via the surface of the surrounding melted powder.

1.10 The melting rate

In arc welding with a consumable electrode, the melting rate of the electrode plays an important role. The melting rate, defined as the mass of electrode material melted and transferred from the electrode to the workpiece per unit time, is determined by the energy transferred to the electrode per unit time, and the energy required to melt a unit mass of electrode material and then heat it to the temperature the droplet has when it leaves the electrode.

As shown in Section 1.8, the arc transfers an amount of heat to the electrode per unit time, which is proportional to the current *I*. In the case where the electrode acts as anode, this amount of heat is equal to:

$$Q_a = \left[V_a + c_a V_{\mathrm{col}} + \varphi_a + \frac{3k(T_{\mathrm{col}} - T_a)}{2e} \right] I \qquad (1.36)$$

where V_a is the anode fall voltage, c_a a constant having a value between 0 and 1, V_{col} the arc column voltage, φ_a the threshold voltage for electron emission of the anode material, k the Boltzmann constant, T_{col} the arc column temperature, T_a the anode temperature, and e the charge of an electron.
In addition to the heat transferred to the anode from the arc, Joule heat is generated in the current carrying part of the electrode, which is equal to:

$$Q_j = \frac{4L\rho}{\pi d^2} I^2 \qquad (1.37)$$

where L is the length of the current carrying part of the electrode (usually referred to as 'stick-out length'), ρ the electric resistivity of the electrode material and d the electrode diameter.
The energy required to melt a unit mass of electrode material and heat it to the temperature the droplet has when it leaves the electrode, is equal to:

$$q = H + (T_d - T_m)C_p \qquad (1.38)$$

where H is the amount of energy to heat and melt a unit mass of electrode material, T_d the temperature of the droplet, T_m the melting point and C_p the specific heat of the liquid metal.
Combining equations (1.36), (1.37), and (1.38), yields the following expression for the melting rate M:

$$M = aI + bI^2 \qquad (1.39)$$

with

$$a = \frac{V_a + c_a V_{col} + \varphi_a + 3k(T_{col} - T_a)/2e}{H + (T_d - T_m)C_p} \tag{1.40}$$

and

$$b = \frac{4L\rho}{\pi d^2 [H + (T_d - T_m)C_p]} \tag{1.41}$$

Equation (1.39) is valid for the (common) case, where the consumable electrode acts as anode. A similar expression can be derived for the case where the electrode acts as cathode.

In the case of SMA welding, equation (1.39) must be corrected for:
- the heat required to melt the electrode coating (negative correction);
- melting of metal powder, when welding with a metal powder containing high-efficiency electrode (positive correction).

Similar corrections must be made in the case of GMA welding with a flux-cored wire and in the case of SA welding.
Figure 1.38 shows the experimentally determined melting rates for SMA welding, GMA welding and SA welding as a function of current. Taking into account the corrections mentioned above, good agreement exists between the experimental results and equation (1.39). Deviations can partly be accounted for by spatter losses (see next section).

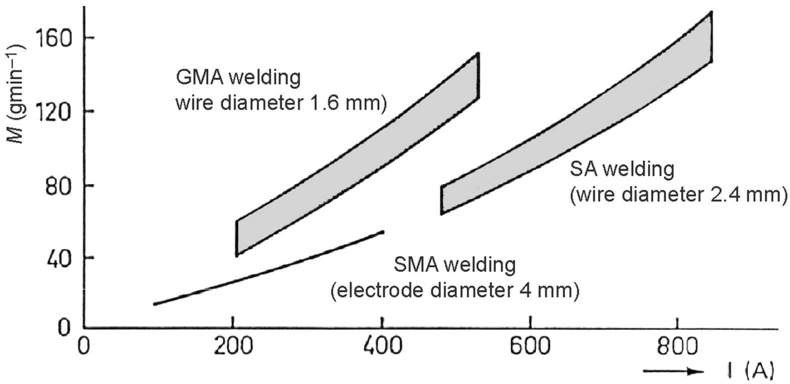

Figure 1.38. Melting rate as a function of current for SMA welding, GMA welding and SA welding.

1.11 Spatter losses

During arc welding, material loss can occur in the form of spattering. The spatters can, if their temperature (heat content) is high enough, attach to the workpiece, the torch nozzle and the contact tube, thus causing problems. Spatters on the workpiece should be removed, while spatters in the nozzle or at the contact tube can hamper gas shielding or wire feeding.

The degree of spattering depends on several factors, including the composition of the shielding gas, the welding parameters, and the composition of the workpiece and the consumables. High-speed images show that spatters can originate from both the electrode and the weld pool.

Spattering originating from the electrode is caused by explosive gas formation in the liquid metal at the tip of the electrode or is due to the fact that the resultant of the forces acting on the droplet is not directed towards the weld pool. Both situations are depicted schematically in Figure 1.39.

Spattering originating from the weld pool is caused by explosion of gas bubbles at the surface of the weld pool and/or by impact of droplets. This is illustrated in Figure 1.40.

Spattering is in particular problematic in the case of short-circuit arc welding. In this case, spattering is the result of explosion of the liquid bridge between the electrode and the workpiece. This explosion is caused by the exponential increase in temperature due to Joule heating in combination with the Lorentz force acting on the neck of the bridge.

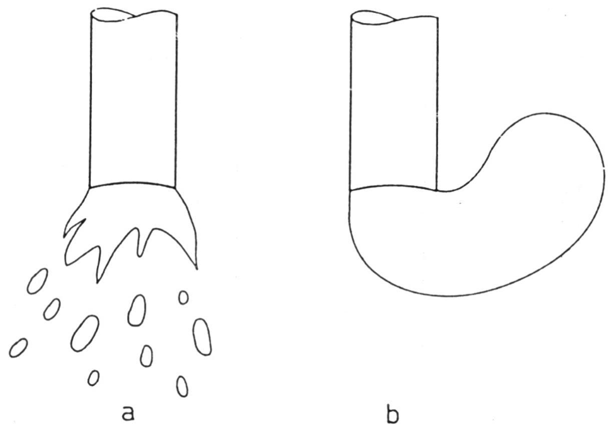

Figure 1.39. Spattering originating from the electrode due to (a) explosive gas formation and (b) sideways directed forces.

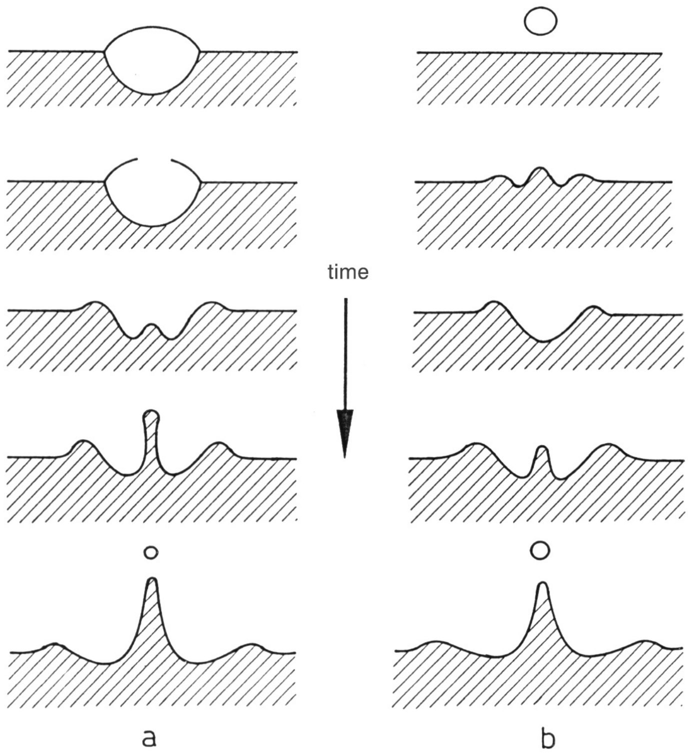

Figure 1.40. Spattering originating from the weld pool due to (a) explosion of gas bubbles and (b) impact of droplets.

1.12 Magnetic effects

As both the arc and the weld pool are electric conductors, the presence of a magnetic field will influence their behaviour.
This magnetic effect is governed by the Lorentz force, expressed by the equation:

$$\vec{F} = \vec{j} \times \vec{B} \tag{1.42}$$

where $\vec{F}$ is the force acting on a unit volume of the arc or the weld pool, $\vec{j}$ the current density in that unit volume and $\vec{B}$ the magnetic induction at that location.

1.12.1 External magnetic fields

Use can be made of external magnetic fields to positively influence the arc welding process. This can be done in different ways, whereby a distinction must be made between transverse magnetic fields and axial magnetic fields.
When an arc is placed in a transverse magnetic field it will move sideward (normal to the plane through the current and the magnetic field), see Figure 1.41a. In the case

of an alternating magnetic field the arc will start to oscillate around its equilibrium position, the maximum deviation being dependent on the current and the magnetic field strength. This magnetically induced arc oscillation can be applied for cladding and can also be used to prevent the occurrence of undercut (see Section 3.7).

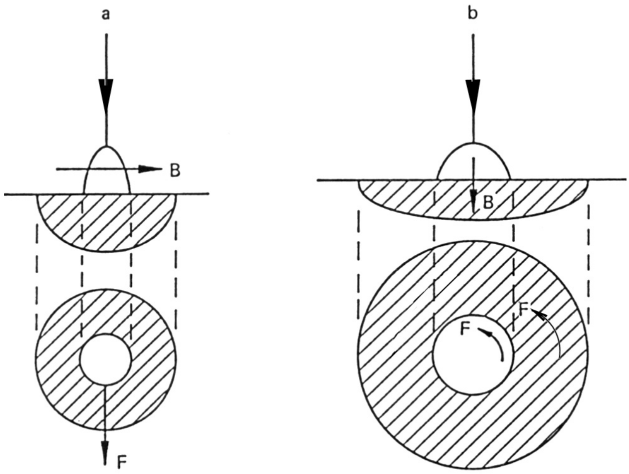

Figure 1.41. Magnetic influence on the arc and the weld pool. a) transverse magnetic field; b) axial magnetic field.

Placing an arc in an axial magnetic field (the axis of the arc parallel to the magnetic field) results in rotation of both the arc and the weld pool (Figure 1.41b). This phenomenon (in the case of the weld pool often referred to as 'magnetic stirring') is due to the presence of a radial component of the current in the arc and the weld pool (the current in the arc and the weld pool diverges). This rotation results in broadening of the arc and to a wider and shallower weld pool. Rotation of the weld pool can also lead to grain refinement of the solidified weld metal. This grain refinement is attributed to the rupture of dendrite tips at the solidification front providing more solidification nuclei.

1.12.2 Magnetic arc blow

Under specific conditions the arc may be affected by its own magnetic field. This influence is called magnetic arc blow, and manifests itself in skewing of the arc. Because this occurs in an irregular way, the arc will continuously change its position (flickering), resulting in an irregular weld bead.

Magnetic arc blow is the result of a non-symmetrical distribution of the self-induced magnetic field around the arc (local concentration of the magnetic field) and may play a role

- in the case of unilateral grounding of the workpiece (Figure 1.42);
- in ferro-magnetic materials close to the edges of the workpiece (Figure 1.43).

Magnetic arc blow occurs in particular when using direct current. When using alternating current, magnetic arc blow is limited, due to eddy currents induced in the workpiece, which partly neutralize the local magnetic field.

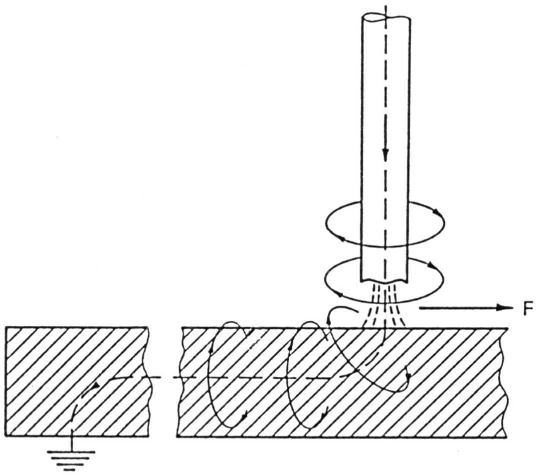

Figure 1.42. Magnetic arc blow due to unilateral grounding of the workpiece.

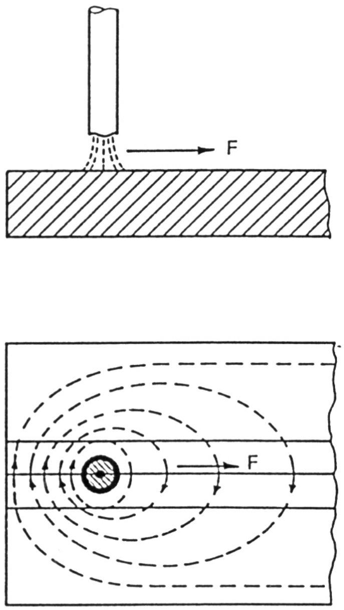

Figure 1.43. Magnetic arc blow at the edge of a ferro-magnetic workpiece.

1.13 Power sources

Arc welding requires a power source capable of delivering a relatively high current (1 – 1000 A) at a relatively low voltage (10 – 50 V). Depending on the application, direct current or alternating current can be used.
As power sources use can be made of

- transformers (alternating current)
- rectifiers (direct current)
- motor-generators (alternating current and direct current)

The development of power sources for arc welding is accelerated over the last few years, mainly because of the growing availability of micro-electronics and control software. This will not be discussed here. The reader is referred to the literature.
The most important technical feature of a power source is its current-voltage characteristic. An example is given in Figure 1.44, together with the current-voltage characteristic of an arc with arc length *l*. The intersection of the two characteristics (the operating point O) determines the current and voltage at which the arc operates under the given conditions. With changing arc length, the characteristic of the arc will shift, and therefore also the operating point. This is shown in Figure 1.44 for both an elongation ($l + \Delta l$) and a reduction ($l - \Delta l$) of the arc length.

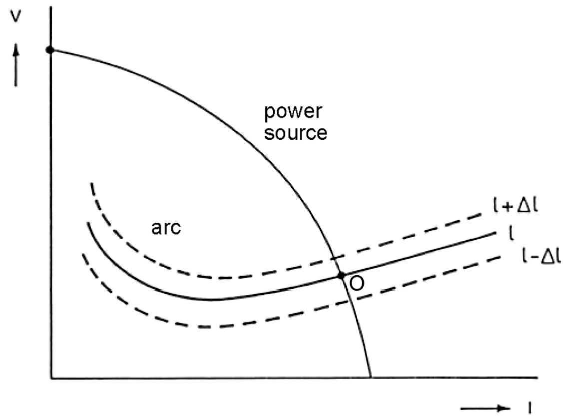

Figure 1.44. Current-voltage characteristics of the power source and the arc.
O = operating point, *l* = arc length.

The figure also shows that when using a power source with a vertical characteristic, the current will remain constant during welding, while when using a power source with a horizontal characteristic, the voltage will remain constant.
For SMA welding, GTA welding and plasma arc welding, a power source with a relatively steep characteristic is usually recommended. Thus, variations in arc length have a limited influence on the current and therefore on the welding results.
For GMA welding, a power source with a horizontal characteristic is more suitable.

Variations in arc length are then corrected by the process itself. This can be clarified as follows. An increase in arc length will lead to a decrease in current and less heat will be transferred to the electrode per unit time, and the melting rate will drop. Because of this, the arc length will decrease until it reaches its original value. A reduction of the arc length will be corrected in a similar way.

In the case of submerged arc welding this automatic correction is too slow, because of the relatively large diameter of the electrode. In view of this, a power source with a drooping characteristic is normally used, combined with a feedback system. With this system, the arc length can be kept within precise limits, via feedback of the arc voltage.

1.14 Robotization of the arc welding process

Over the last years the trend in high productivity and high quality arc welding has been particularly directed towards process automation. This has led to the development and increased use of robotic systems for GTA and GMA welding.

A typical robotic system for GMA welding is shown schematically in Figure 1.45 and consists of a robot for positioning the welding torch, a control system for manipulation of the robot arm, a workpiece manipulator, and welding equipment. The robot(arm) preferably has six degrees of freedom: three for positioning and three for orienting the welding torch. The possibilities of such a robotic system, however, are limited because only a predefined welding path can be followed.

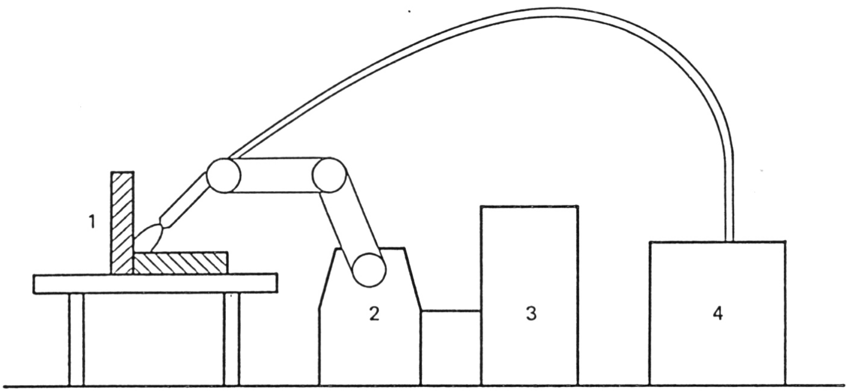

Figure 1.45. Schematic representation of a robotic system for GMA welding.
1) workpiece, 2) robot, 3) control unit, 4) power source with wire feeding unit.

For more advanced robotic systems sensors are required, which are able to continuously monitor the welding process, making it possible to adapt the welding conditions in real-time.

Sensors for welding robots can roughly be divided into two types: sensors for seam tracking and sensors for process control.

Sensors for seam tracking are based on the continuous measurement of the position of the welding torch with respect to the welding seam, whereas with sensors for process control real-time information is obtained about the geometry of the weld pool.
The most important sensors currently used in practice or in development are briefly described below.

1.14.1 Tactile sensors

Tactile sensors are the first group of sensors that became available for arc welding robots. The tactile sensor consists of a sensing element, usually in the form of a needle, which is connected to the welding torch and follows the weld groove during welding. If the groove deviates from a predefined path, the needle moves to a different position. This movement is then converted into a signal, which is fed back to the robot controller. It is evident that tactile sensors are only suitable for seam detection and seam tracking.

1.14.2 Pneumatic sensors

In pneumatic sensors, the output signal is a static gas pressure, which is a measure of the distance between the sensor and the workpiece. Because only one distance is measured, two or more sensors must be combined to track a weld groove. When using this sensor one must be careful not to disturb the gas shielding around the weld pool.

1.14.3 Ultrasonic sensors

For monitoring the distance to the workpiece, ultrasonic sensors with a combined sending and receiving unit can be used. The time delay between sending and receiving of an ultrasonic pulse is a measure of the distance. It is also possible to determine the position of the weld pool in the workpiece by placing the ultrasonic sensor on the surface of the workpiece and sending and receiving sound pulses through the material. An advantage of this approach is that also information about the geometry of the weld pool can be obtained.

1.14.4 Inductive sensors

Inductive sensors use an alternating magnetic field to generate magnetic induction in the workpiece, which can then be detected by means of a measuring coil. The signal detected is a measure for the distance to the workpiece. A distinction can be made between sensor systems using high and systems using low frequencies. Sensor systems using low frequencies are only suitable for ferro-magnetic workpieces. In sensor systems using high frequencies, the effect of eddy currents is used. These systems are therefore suitable for all metals.

1.14.5 Arc sensors

In arc welding, the arc itself can also be used as a sensor. The principle of the arc sensor is based on the fact that a simple (almost linear) relationship exists between the arc length and the current in the case of a horizontal power source characteristic, and between the arc length and the arc voltage in the case of a vertical power characteristic. By measuring the arc current or the arc voltage the arc length, and thus the position of the welding torch relative to the workpiece, can be determined. The principle of arc sensing is schematically shown in Figure 1.46.

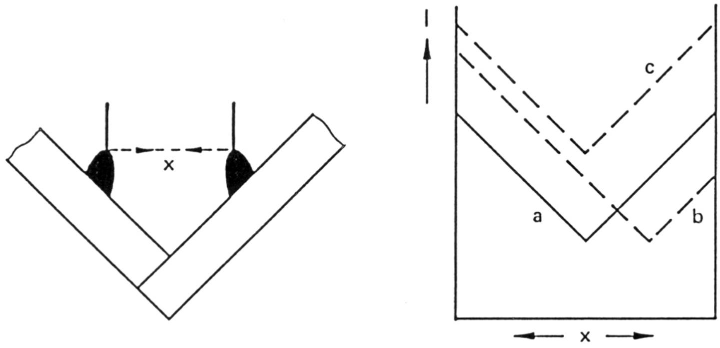

Figure 1.46. Schematic representation of the operating principle of an arc sensor: a - correct position; b - horizontal deviation; c - vertical deviation.

Arc sensing can also be used for adaptive control of weld (pool) penetration.
In this approach the weld pool is triggered into oscillation by current pulses superimposed on the welding current and the frequency of this oscillation is determined by measuring the arc voltage variations.
This oscillation frequency provides information about the size and penetration depth of the weld pool, which after feed-back can be used for adaptive control of the welding parameters.

1.14.6 Optical sensors

In optical sensors, an image is formed of the weld groove and/or the weld pool. In most cases, an external light source is required, uniformly illuminating the location to be monitored, or providing a structured pattern of light at this location. Sometimes, instead of an external light source, the radiation of the arc or the weld pool is used. Detection can vary from measuring the reflection of several points to registering the total image. Different types of optical sensors are already used in practice.

1.14.7 Temperature sensors

By measuring the distribution of the temperature in the workpiece, it is possible to obtain real-time information about the position and the geometry of the weld pool. Usually the temperature is measured by infra-red detection. For seam tracking it is often sufficient to measure at two points on either side of the weld groove. By scanning the temperature of the weld pool, its geometry can be characterized, enabling in-process control.

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