2

Welding Technology

2.1 Gas Tungsten Arc Welding (GTAW)

The gas tungsten arc welding (GTAW) process is based on the electric arc established between a non-consumable electrode of tungsten and the work-pieces to be joined. Part of the heat generated by the electric arc is added to the work-pieces, promoting the formation of a weld pool. The weld pool is protected from air contamination by a stream of an inert gas (Ar or He) or a mixture of gases.

2.1.1 Introduction

This process is also known as tungsten inert gas (TIG), although small amounts of non-inert gases may be used in the shielding mixture, such as hydrogen or nitrogen. Figure 2.1 illustrates the principal elements of the conventional process.

Autogenous GTAW welding (without filler metal) is used in thin square edged sections (2mm), while V and X type edge preparations are needed in thicker sections. In this case, the addition of filler metal is necessary. This process is extensively used for welding thin components of stainless steel, aluminum, magnesium or titanium alloys as well pieces of carbon and low alloy steels [1],[2].

Heat input in GTAW does not depend on the filler material rate. Consequently, the process allows a precise control of heat addiction and the production of superior quality welds, with low distortion and free of spatter. It is less economical than other consumable electrode arc welding processes, due to its lower deposition rate, and it is sensitive to windy environment because of the difficulty in shielding the weld pool. Besides it shows low tolerance to contaminants on filler or base metals.

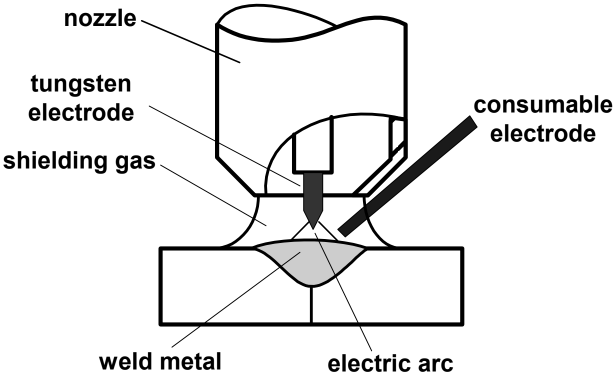

Figure 2.1. Diagrammatic sketch of the gas tungsten arc welding process (GATW)

The autogeneous process is readily used in robotics, although special techniques are needed when it is necessary to add filler metal to the weld pool.

2.1.2 Welding Equipment

In this section the relevant aspects related to the welding equipment used with the GATW process will be reviewed, with the objective of exploring the implications for automatic robotic welding.

2.1.2.1 Power Sources

Power sources for GTAW are generally of the constant current type with drooping volt-ampere static curves, as illustrated schematically in Figure 2.2. Light weight transistorized direct current power sources are currently used, being more stable and versatile than the old thyristor-controlled units [3]. In rectifier-inverter power sources the incoming AC current is rectified and then converted into AC current at a higher frequency than that of the mains supply, in the inverter. Afterwards high voltage AC current is transformed into low voltage AC current suitable for welding, in the transformer, and then rectified, as shown schematically in Figure 2.3. The aim to increase the current frequency is to reduce the weight of the transformer and other components of the source such as inductors and capacitors.

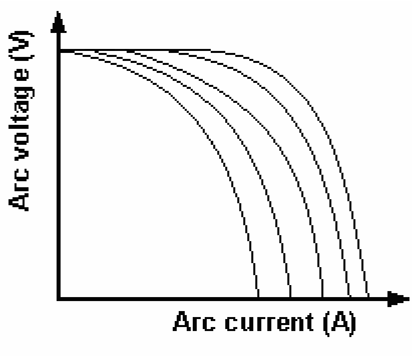

Figure 2.2. Plot of the arc voltage ***vs*** current voltage for GTAW power sources

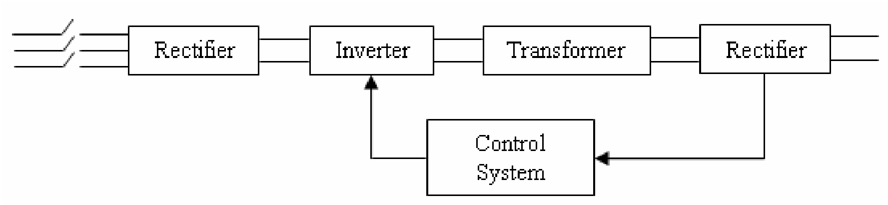

Figure 2.3. Sketch of the inverter principle of the power sources

2.1.2.2 Welding Torch

The welding torch holds the non-consumable electrode, assures the transfer of current to the electrode and the flow of shielding gas to the weld pool. Torches with welding regimes up to 200 A are generally gas-cooled and those with continuous operation between 200 and 500 A are water-cooled. Figure 2.4 shows an exploded view of a water-cooled torch.

2.1.2.3 Non-consumable Electrodes

Non-consumable electrodes are composed of pure tungsten or of tungsten alloys. Pure tungsten electrodes can be used with DC but are more sensitive to contamination, have lower service life-cycle and exhibit higher tip deterioration than alloyed electrodes. These electrodes can be used in welding of aluminum and magnesium alloys on AC.

Thoriated tungsten (2% ThO_2) electrodes are widely used in industrial applications due to its excellent resistance to contamination, easy arc starting and stable electric arc. Concerns about safety, because thorium oxide is radioactive, led to the development of other electrodes containing small proportions (around 2%) of simple earth rare elements such as lanthanum, yttrium and cerium or even mixtures of several elements [4],[5]. These electrodes have better operational characteristics than thoriated electrodes and can be used in welding carbon and stainless steels, nickel and titanium alloys. Zirconiated tungsten electrodes are excellent for AC due to its good arc starting, high resistance to contamination and small tip shape deterioration.

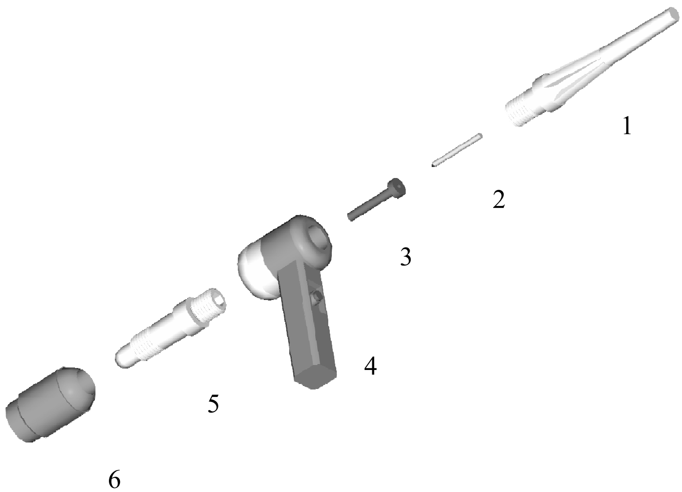

Figure 2.4. Exploded view of a torch: back cap – 1; electrode – 2; collet – 3; handle – 4; collet body – 5; nozzle – 6

These electrodes are available in diameters between 0.5 and 12 mm, although the most usual are up to 4 mm in diameter, being the normal length between 50 and 175 mm. The selection of the electrode diameter to use depends on the plate thickness to be welded, being in general similar to plate thickness.

2.1.2.4 Arc Striking Techniques

Arc initiation by touch striking was used formerly in manual GTAW, but this technique is very sensitive to tungsten contamination, adversely affecting the service life of the electrode. High-frequency-high-voltage (*e.g.* 3 kV at 5 MHz) supplies are currently used in arc striking and AC arc stabilization in manual GTAW systems [3]. This arc starting technique usually produces interference in electronic equipment in the vicinity of the power source.

Programmed touch striking is an alternative technique developed for automatic systems. In this technique current and voltage are limited when electrode touches in the work-piece, in order to prevent electrode contamination. A pilot arc starting can also be used to initiate the main electric arc, though a more complex torch is needed.

2.1.2.5 Shielding Gas Regulator

The regulator is a device that reduces source gas pressure to a constant working pressure, independently of source pressure variations. Pressure reduction can be made in one or two stages. Regulators in two stages give in general more stable output flow.

2.1.3 Process Parameters

In this section the relevant parameters for the GTAW process will be reviewed with the double objective of presenting them and showing that they can certainly be used for automatic robotic welding.

2.1.3.1 Current

Current has direct influence on weld bead shape, on welding speed and quality of the weld. Most GTAW welds employ direct current on electrode negative (DCEN) (straight polarity) because it produces higher weld penetration depth and higher travel speed than on electrode positive (DCEP) (reverse polarity). Besides, reverse polarity produces rapid heating and degradation of the electrode tip, because anode is more heated than cathode in gas tungsten electric arc.

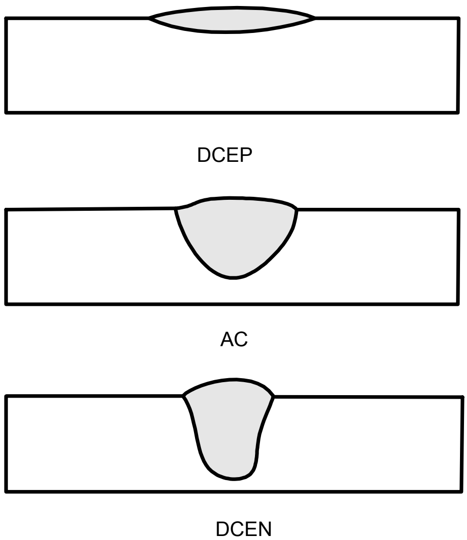

Figure 2.5. Effect of current and polarity on weld bead shape

Reverse polarity may be of interest in welding aluminum alloys because of the cathodic cleaning action of negative pole in the work-piece, that is the removal of the refractory aluminum oxide layer. However alternating current is better adapted to welding of aluminum and magnesium alloys, because it allows balancing electrode heating and work-piece cleaning effects. Weld penetration depth obtained with AC is between depth obtained with DCEN and DCEP, as illustrated in Figure 2.5.

Square wave AC is nowadays being used instead of the normal sine wave because it facilitates the assistance of the arc re-strike each half cycle and allows adjusting of the arc cleaning effect or the penetration depth. Cleaning action is improved by increasing duration of the electrode positive half cycle. The increase in penetration depth is given by increasing the duration of the electrode negative half cycle, as shown schematically in Figure 2.6.

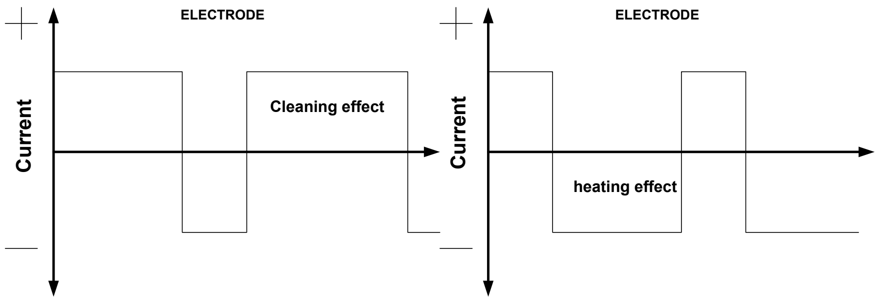

Figure 2.6. Influence of the balance between alternate half cycles on GTAW

Pulsed DC current with low-frequency (1-10 Hz) is being used to reduce weld distortion, to improve tolerance to joint preparation and to cast-to-cast variations. Current magnitude and duration of the pulses are determined by material family and thickness of the component to be welded and are related by Equation 2.1 [3],

$$I_p \cdot t_p = K \qquad 2.1$$

where, I_p is the pulse current, t_p is the pulse time and K is a constant. Background current and time are selected in order to allow solidification of metal between pulses. This current is used in welding of stainless steels.

High-frequency pulsed current (5-30 kHz) improves arc stiffness, increasing penetration depth and maximum welding speed and decreasing formation of porosity in the weld metal. This current is advantageous in automatic welding applications.

2.1.3.2 Welding Speed

The effect of increasing the welding speed for the same current and voltage is to reduce the heat input. The welding speed does not influence the electromagnetic force and the arc pressure because they are dependent on the current. The weld speed increase produces a decrease in the weld cross section area, and consequently penetration depth (*D*) and weld width (*W*) also decrease, but the *D/W* ratio has a weak dependence on travel speed [7]. These results suggest that the travel speed does not influence the mechanisms involved in the weld pool formation, it only influences the volume of melted material. Normal welding speeds are from 100 to 500 mm/min depending on current, material type and plate thickness.

2.1.3.3 Arc Length

The arc length is the distance between the electrode tip and the work-piece. The arc length in GTAW is usually from 2 to 5 mm. If the arc length increases, the voltage to maintain the arc stability must increase, but the heat input to work-piece decreases due to radiation losses from the column of the arc. Consequently, weld penetration and cross section area of melted material decrease with increasing arc length.

2.1.3.4 Shielding Gases

Shielding gases are used in GTAW in order to prevent atmospheric contamination of the weld metal. This contamination can produce porosity, weld cracking, scaling and even change in the chemical composition of melted material. Besides shielding gas also has a large influence on the stability of the electric arc. Gases with low ionization potential facilitate the ignition of the electric arc and those with low thermal conductivity tend to increase the arc stability.

Argon is the most used GTAW shielding gas. It has low ionization potential and is heavier than air, providing an excellent shielding of the molten weld pool. Furthermore it is less expensive than helium, the other inert shielding gas used in the process. Argon is used in welding of carbon and stainless steels and low thickness aluminum alloys components.

For welding thick aluminum work-pieces and other high-conductive materials, such as copper alloys, helium is recommended because it has higher ionization potential than argon, needing higher voltage for arc initiation and maintenance, but producing higher heat-input. Helium or helium/argon (30-80% He) mixtures allow increased welding speed and improved process tolerance.

Mixtures of argon with up to 5% of hydrogen are frequently used in welding of austenitic stainless steels. Hydrogen increases arc-voltage and consequently heat-input, increasing weld penetration and weld travel speed, as well improving weld appearance [6]. Argon/hydrogen mixtures are also used in welding of copper-nickel alloys.

Argon is also used as back side shielding gas, mainly in welding of stainless steels, aluminum alloys and reactive metals.

Flow rates of shielding gases depend on weld thickness, being 4-10 l/min for argon and 10-15 l/min for helium, because it is lighter than argon, and consequently less effective in shielding.

Gases with a purity of 99.995% are used in welding most of the metals, though reactive materials such as titanium need contaminant level less than 50 ppm.

2.1.3.5 Filler Metals

Filler metals are generally used for plate thickness above 2 mm, having chemical composition similar to that of the parent material. Filler metal diameter is between 1.6 and 3.2 mm and in automatic systems is normally added cold from a roll or a coil.

2.1.3.6 Electrode Vertex Angle

The non-consumable electrode angle influences the weld penetration depth and the weld shape [7]. Electrode angles between 30º and 120º are used. Small angles increase arc pressure and penetration depth but have high tip shape deterioration. Electrode angles from 60º to 120º maintain tip shape for longer periods and give welds with adequate penetration depth-to-width ratio.

2.1.3.7 Cast-to-cast Variation

Cast-to-cast variation refers to variation observed in penetration of welds produced in the same welding conditions in several batches of austenitic stainless steel with nominally identical composition. These changes in the weld bead shape are attributed to variation in proportion of trace elements in the material, such as sulphur, calcium and oxygen. Variations in trace elements seem to affect surface tension and metal flow into the pool [8]. Weld pool shape is also affected by electromagnetic forces, arc pressure and thermo capillarity forces [9]. To minimize this problem several strategies have been adopted such as the use of higher currents or of pulsed current, the application of adequate shielding gases or the application on plate surface of flux coatings containing active ingredients [10].

2.1.4 Process Variants

GTAW is regarded as a high quality process for welding thin metals using low travel speed and low electrode deposition rate, requiring highly skilled personnel in manual welding. Variants developed seek to improve productivity, mainly deposition rate, penetration depth and welding speed. These variants are implemented in automatic or robotic systems.

Hot-wire GTAW is a variant where a heated filler wire is fed to the rear of the melted weld pool at a constant rate, as represented schematically in Figure 2.7. Filler wire is resistance heated close to melting point using mainly AC power sources, in order to minimize magnetic disturbance of the electric arc. Deposition rates up to 14 kg/h can be attained with this process. It has been used in heavy wall fabrication, maintaining high joint integrity [11].

The use of a dual-shielding GTAW technique, see Figure 2.8, where an additional concentric gas shield gives an increase in constriction and stiffness of the electric arc, may be used to increase welding speed and penetration depth [12]. Constriction of the arc is produced by the external cold gas flow which decreases temperature of the outer part of the arc, decreasing the arc cross section where current flow occurs, consequently increasing current density and temperature. Electrode gas and annular gas may be of the same or of different compositions, such as Argon plus 5% hydrogen for internal gas and argon for external gas when welding austenitic stainless steels. For currents above 335A keyhole welding is obtained and the process may becomes sensitive to the process parameters. This technique also tends to increase the risk of undercut [3].

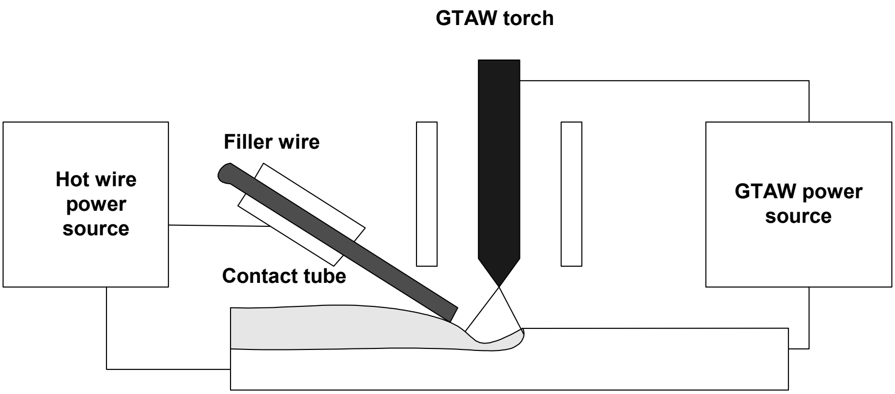

Figure 2.7. Schematic representation of a GTAW hot wire system

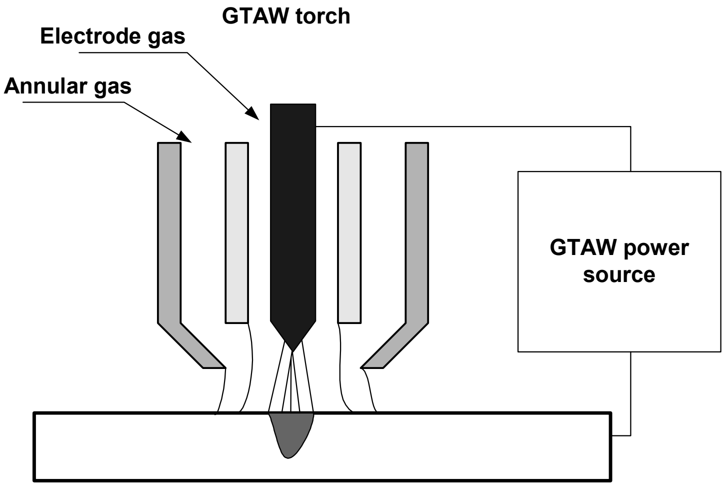

Figure 2.8. Schematic representation of dual-shielding GTAW system

Very high currents (I > 300 A) may also be used in a conventional automated GTAW process to increase the penetration depth, but defects may form and the process becomes unstable above 500 A. The keyhole mode gas tungsten arc welding process, which was developed a few years ago, seems to be suitable for ferrous and non-ferrous materials in the range from 3 to 12 mm [13]. However, this keyhole technique is extremely sensitive to arc voltage, and loss of material may occur through the keyhole vent.

2.2 Gas Metal Arc Welding (GMAW)

In the gas-metal arc welding (GMAW) process n electric arc is established between a consumable electrode, fed continuously to the weld pool, and the work-piece. Initially the weld pool was shielded by an inert gas, giving the process the popular designation of metal inert gas (MIG). Nowadays active gases such as carbon dioxide or mixtures of inert and active gases are also used and metal-active gas (MAG) is a common process nomenclature in this case. The designation GMAW includes all these cases. A schematic representation of the process is shown in Figure 2.9.

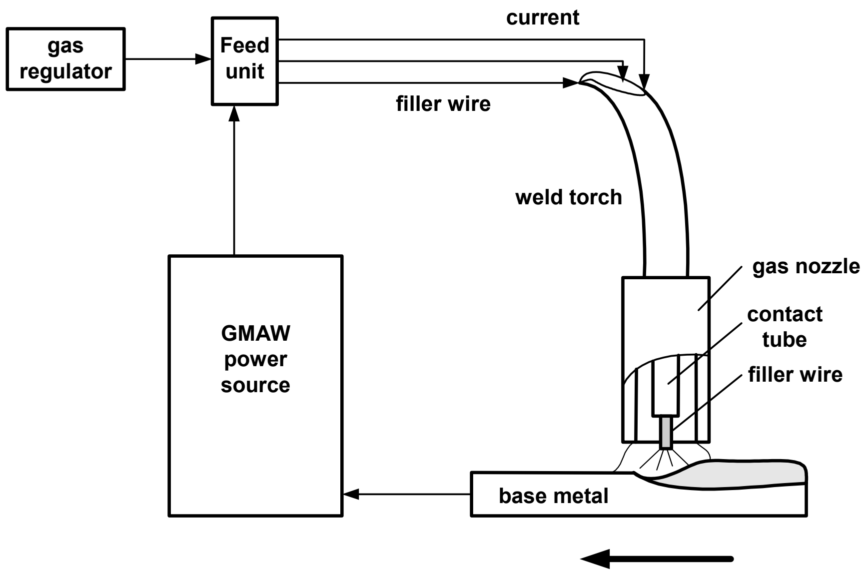

Figure 2.9. Schematic representation of gas metal arc welding process (GMAW)

2.2.1 Introduction

This process is widely used in industrial applications due to its numerous benefits. It can weld almost all metallic materials, in a large range of thicknesses (above 1 mm up to 30 mm or more) and is effective in all positions. GMAW is a very economic process because it has higher speeds and higher deposition rates than for example the manual metal arc process, and does not require frequent stops to change electrodes, as is the case of this former process. In addition, minimal post weld cleaning is needed because slag is almost absent. Less operator skill is required than for other conventional processes because electrode wire is fed automatically (semi-automatic process) and a self-adjustment mechanism maintains the arc length approximately constant even when the distance weld torch to work-piece varies within certain limits. These advantages make the process very well adapted to be automated and particularly to robotic welding applications.

The process is sensitive to the effects of wind, which can disperse the shielding gas, and it is difficult to use in narrow spaces due to the torch size. Problems such as lack of shielding, irregular wire feeding, unstable arc, burn-back or even weld discontinuities (porosity, incomplete penetration, excessive melt-through, undercutting or cracks) can occur during welding [14].

2.2.2 Welding Equipment

Basic equipment for conventional GMAW is consists of the power source, the electrode feed unit, the welding torch and the shielding gas regulator, as represented schematically in Figure 2.9.

2.2.2.1 Power Source

Most common GMAW power sources are of the inverter type with an architecture similar to that represented in Figure 2.3, but providing a constant-voltage output. A constant-voltage power source used in conjunction with a constant speed wire feeder can provide self-adjustment and stabilization of the arc length, in order to compensate for the variations in the torch to work-piece distance that occur mainly during manual welding operations. In a power source with approximately constant-voltage characteristics any change in the arc length is compensated by the modification of the weld current and consequently of the burn-off behavior of the electrode. Figure 2.10 illustrates the effect of increasing the arc length from L_1 to *L2*, which corresponds to an increase of the torch to work-piece distance. This increase of arc length produces an increase of the arc voltage and consequently a decrease of the weld current from I_1 to I_2 and of the burn-off rate from B_1 to B_2. As the wire feed speed is constant and burn-off decreases the arc tends to assume the initial length.

In addition these machines provide slope control of the power source characteristics and of the inductance in order to control spatter in short-circuiting transfer [3]. Inductances introduced in the output circuit reduce the rate of rise of current during the short-circuiting, reducing in this way the risk of explosion of metal droplets. In the case of thicker electrodes, which show a small variation of burn-off rate with current, or for materials having high conductivity, such as aluminum, process control is achieved by using a variable-speed wire feed unit that reacts to the arc length changes by adjusting the electrode feed speed.

GMAW inverters are also used to generate pulsed current with pulsed repetition rates (PRR) (number of pulses per second) typically between 100 and 200 PRRs [15]. Pulsed parameters are defined by algorithms in the controller. New synergic pulsed GMAW inverters can control melting rate through the modulation of the pulse shape and of the pulse frequency, being the process managed by a microprocessor [3].

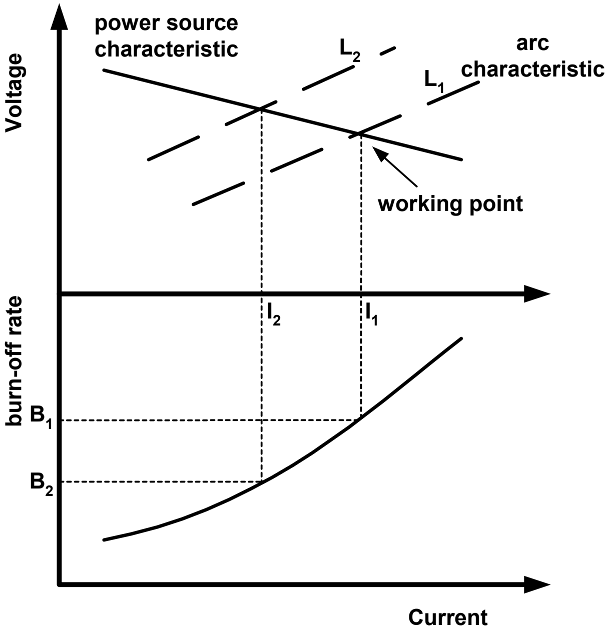

Figure 2.10. Self-adjustment mechanism with a constant-voltage power source. Arc length $L_1 > L_2$

2.2.2.2 Electrode Feed Unit

The electrode feed unit and the welding control mechanism are generally furnished in one integrated package. The electrode feed unit pulls the electrode from the reel and pushes it through a conduit to the welding torch (gun). This unit is composed of a direct-current motor, that varies the motor speed over a large range, a gear box and two pairs of rolls with a pressure adjusting screw and wire guides, that transmit mechanical energy , straighten and guide the electrode. Knurled rolls are used for hard materials, such as steel electrodes, and V and U type rolls are used for softer materials, such as aluminum electrodes. For soft electrodes or long conduits push-pull systems can be used too. Theses systems are composed of two feed units, one that is close to the wire reel that pushes the electrode, and the other unit in the torch that pulls the electrode. In automatic and robotic welding systems the electrode is fed from a spool (15-18 kg) or large drum (200-475 kg) to minimize wire supply changing. Normally, the electrode feeder for robotic welding is mounted separate from the power supply.

The welding control mechanism regulates not only the electrode feed speed and the start and stop of the electrode but also the delivery of shielding gas, current and cooling water (when necessary) to the torch. Creep start, gas pre-flow and post-flow, hot start, crater filling and adjustable burn-back time can frequently be programmed in this unit. Memory for pre-programs and for set parameters is frequently available in this unit.

When the torch cable is externally attached to the robot arm it is exposed to work-piece interference and to premature wear. Modern robotic systems can include special arms with internal cabling, in order to prevent interference, increasing cable life.

2.2.2.3 Welding Torch

Main functions of the welding torch are to furnish the electrode with electrical current and direct the electrode and gas flow to the work-piece. Main components of the welding torch are the contact tube, where the current is transmitted to the electrode, the nozzle, which provides a laminar gas flow to the weld pool, the torch switch, which sends signals to the feed unit, and the handle. The handle supports the gas and water (if necessary) tubes, the electrode guide tube and cables for current and signals. MIG torches for low current and light duty cycle (up to 60%) are gas cooled and torches for heavy duty cycle (up to 100%) and high current are water cooled. Robotic torches are in general water cooled, but if gas cooled torches are used they must be larger than manual torches. Alternatively air cooled torches, which use shop compressed air, can be applied instead of water cooled torches [16]. Robotic torches usually have emergency-stop capability to prevent damage to the robot arm and the welding torch in the event of a collision. They are also provided with automatic cleaning, that may include a pressurized air system for blowing spatter out of the nozzle, a reamer for cleaning the internal nozzle structure and an anti-spatter fluid delivery system.

Twin-wire GMA robotic welding torches can be used to reach higher deposition rate and welding speed. In this case a side-by-side configuration is used, with both wires being fed to close contact tips, in order to give a single weld pool.

2.2.3 Process Parameters

Welding parameters affect the way the electrode is transferred to the work-piece, the arc stability, spatter generation, weld bead geometry and overall weld quality. The main parameters of the process are current, voltage, travel speed, electrode extension and electrode diameter, though others, such as electrode orientation, electrode composition and shielding gas, also have direct influence on the metal transfer mechanisms. These parameters are not independent. The current and voltage, for example, are correlated by the arc characteristic curves shown in Figure 2.10; voltage depends not only of the arc length but also on the electrode extension and on the shielding gas.

2.2.3.1 Current

Direct current electrode positive (DCEP) is the most used current in GMAW because it gives stable electric arc, low spatter, good weld bead geometry and the greatest penetration depth.

For low currents and voltages in combination with active shielding gases or mixtures containing active gases, dip or short-circuiting transfer is obtained. Metal is transferred to the work-piece by bridging at frequencies usually above 100 Hz. This metal transfer mode gives low heat input, being suited for welding thin sections and for positional welding.

Globular transfer is obtained for currents and voltages somewhat above those of the dip transfer, if inert shielding gases are used. When carbon dioxide shielding gas is used this metal transfer mode is obtained only for high currents and voltages. Globular transfer is characterized by large drops, with size identical to the electrode diameter or higher, transferred at low frequency. This mode of transfer can be used in a downward direction, due to the predominance of gravitational forces during metal transfer.

The utilization of relatively low current can give insufficient penetration and excessive weld reinforcement, occasioned by poor wetting action of the weld metal. Globular repelled transfer can be found when electrode negative polarity is used with solid wire, but this mode of transfer has no industrial application due to poor stability and high spatter levels which result.

For currents and voltages higher than for globular transfer, projected spray transfer occurs when argon-rich shielding is used. It arises for currents above spray transition current, which depends on the electrode material, shielding gas and electrode diameter. It is approximately 240 A for 1.2 mm diameter carbon steel electrodes with argon/5% CO_2 shielding [3]. This mode of transfer is characterized by very small drops projected onto the work-piece at a very high frequency, up to 350 drops per second, presenting low spatter level. As high currents are used high heat inputs to the work-pieces are reached, producing large weld pools with deep penetration. This type of metal transfer is attractive when high deposition rate welds in thick materials in a downward direction are to be performed. However it presents limited capacity in positional welds, due to the effect of gravity forces. For even higher currents and voltages, streaming spray transfer is obtained, but it has no industrial application due to high weld pool turbulence caused by the increase of the electromagnetic forces.

Drop spray transfer mode can occur in the transition between globular and projected spray transfer, in a restricted operating range. This metal transfer mode is characterized by a very efficient detachment of small drops from the electrode, which are projected onto the work-piece at high velocity and with low spatter level. This type of transfer is difficult to regulate in conventional DC power sources but can be achieved using pulsed transfer techniques.

Pulsed current allows projected spray transfer for mean currents below spray transition current, improving positional capabilities and operating tolerances of the process. Details concerning the control of the metal transfer modes in the arc are given in Chapter 3.

2.2.3.2 Voltage

Arc voltage is directly related to current, as indicated above, and with arc length, increasing with it. Voltage also depends on the shielding gas and electrode extension. The increase of arc voltage widens and flattens the weld bead. Low voltages increase the weld reinforcement and excessively high voltages can cause arc instability, spatter, porosity and even undercut.

2.2.3.3 Welding Speed

Increase in the welding speed gives a decrease in the linear heat input to the work-piece and the filler metal deposition rate per unit of length. The initial increase in welding speed can cause some increase in penetration depth, because the arc acts more directly in the parent material, but further increase in speed decreases penetration and can cause undercut, due to insufficient material to fill the cavity produced by the arc.

2.2.3.4 Electrode Extension

The electrode extension is the electrode length that is out of the contact tube. The increase of electrode extension, produced by the increase of the torch distance to the work-piece for a specific parameters set, increases electrode melting rate because of the Joule effect. Electrode extension ranges from 5 to 15 mm for dip transfer, being higher (up to 25 mm) for the other transfer modes.

2.2.3.5 Shielding Gas

Shielding gases have an effect on arc stability, metal transfer mode, weld bead shape and melting rate. Gases used in GMAW can be pure gases, binary, ternary and exceptionally quaternary mixtures. Common pure gases are argon, helium and carbon dioxide. The first two are inert gases and are used principally in welding of light alloys, nickel, copper and reactive materials. Helium has a higher ionization potential than argon, providing larger weld pools, but is more expensive. Carbon dioxide is an active gas and is used in welding of carbon steels. It produces high levels of spatter but provides high penetration depth.

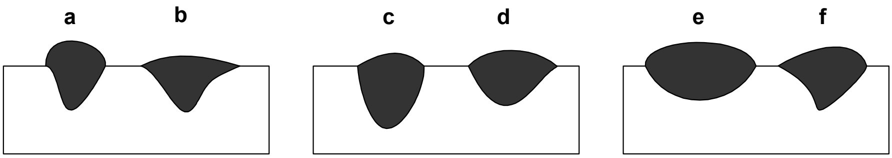

Figure 2.11. Effect of shielding gas on weld geometry. Argon – **a**; argon+oxygen – **b**; CO_2 – **c**; argon+CO_2 – **d**; helium – **e**; argon+helium – **f**

Binary mixtures are commonly argon/carbon dioxide (up to 20% CO_2), argon/oxygen (up to 5% O_2) and argon/helium (up to 75% He). The first is used in the welding of carbon and low alloy steels, the second of stainless steels and the third of nonferrous materials. The addition of oxygen or carbon dioxide to argon stabilizes the welding arc and changes the bead shape [17], as illustrated in Figure 2.11. The objective of adding helium to argon is to increase heat input and consequently welding speed, but also to reduce the incidence of weld porosity.

The most common ternary mixtures are argon/oxygen/carbon dioxide, used in welding of carbon steels, argon/helium/carbon dioxide and argon/carbon dioxide/hydrogen, used in welding stainless steels. Ternary mixtures are intended for improving weld bead profile, increasing tolerance to material contamination and promoting higher travel speeds.

2.2.3.6 Electrode Diameter

Chemical composition of the electrodes is similar to that of the materials being welded. Most usual electrode diameters are 0.8, 1, 1.2 and 1.6 mm. Electrodes of lower diameter are used for thin materials. Electrodes of 1.2 and 1.6 mm diameters are utilized in welding thicker materials and need higher currents, which produce larger weld pools. Electrodes of 1.6 mm diameter are not recommended for positional applications.

2.2.4 Process Variants

Flux cored arc welding (FCAW) is a process similar to GMAW but uses a tubular flux cored electrode as the consumable instead of a solid electrode, as shown in Figure 2.12. Flux has several functions which are deoxidization, alloying, gas generation and formation of a protective slag. The process has two variants, these being the gas-shielding FCAW process, that uses an external shielding gas to assist in shielding the arc and the weld pool from the air, and the self-shielded FCAW process that works without external shielding. Flux-cored electrodes offer several advantages such as higher deposition rate than solid electrodes, because of higher current density of tubular electrodes, alloying addition from the flux, slag shielding and improved arc stabilization, more tolerance to rust and scale than conventional process and the need for less skilled personnel.

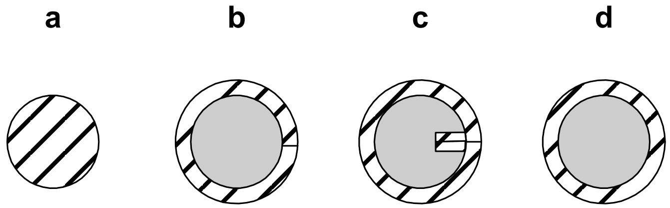

Figure 2.12. Cross section of common flux-cored electrodes. Solid electrode – **a**; flux-cored electrodes – **b**, **c** and **d**

The main limitations of flux-cored electrodes are the large quantity of fumes generated, which is potentially toxic, and the need for removing slag, particularly in multipass welds. Flux–cored electrodes are more expensive than solid electrodes but the difference in cost of the consumable is compensated by the decrease in labor costs because they have higher burn-off rate than solid electrodes.

Flux-cored electrodes of 1 and 1.2 mm diameter can be used in positional work in contrast to electrodes of 1.6, 2.4 and 3.2 mm that must be used in flat and horizontal positions. In the last few years electrodes have been developed mainly for welding carbon and low alloy steels as well as for stainless steels and for hardfacing applications. For steels, CO_2 and argon/CO_2 mixtures are used as shielding gases.

Constant-voltage direct current machines are recommended for FCAW processes, though output rates should be higher than for conventional process. For semi-automatic process outputs, between 400 and 600 A are recommended while for mechanized and robotic systems power sources with outputs, up to 1000 A may be required for some applications. Knurled feed rollers are generally used to feed flux-cored electrodes in order to avoid crushing the electrode, even when using low pressure. Water-cooled torches are used mainly in automatic and robotic welding for currents above 300 A when argon-rich shielding mixtures are used.

MIG/MAG tandem and multi wire welding can give a significant increase in welding speed and disposition rate and also influence the weld geometry [19].

The GMAW process can be used in combination with other welding processes such as plasma arc welding (PAW) or laser welding (LW) to improve deposition rate, welding speed, flexibility and productivity [20],[21]. Limitations of these processes are the high capital cost and complexity in setting optimal welding parameters.

The AC pulsed GMA process is currently under development for robotic welding applications. It is well suited to the welding of aluminum alloys, giving high-quality and productivity in welding of thin-sheet joints. Moreover it extends the root opening tolerance and reduces work-piece distortion, during the welding cycle [58].

2.3 Laser Beam Welding (LBW)

A laser consists of a high-power coherent monochromatic light beam which can be focused to a small spot, producing a very high energy density. Laser is the acronym for "*light amplification by stimulated emission of radiation*". A laser beam is produced by stimulating emission of electromagnetic radiation in specific solid or gaseous materials. Atoms of these materials are moved to higher energy levels by absorbing stimulating energy, producing a population inversion, that is material is brought into a condition in which population of atoms at a higher energy level is greater than that at lower level. These atoms decay by spontaneous emission of photons, which can generate more photons by stimulating emission from other excited atoms, producing the amplification of the laser light. Laser light sources have reflecting mirrors incorporated (see Figure 2.13) which reflect photons back for further light amplification.

2.3.1 Introduction

The most popular lasers for welding are the solid-state lasers of neodymium-doped yttrium aluminum garnet (Nd:YAG), generally pulsed wave, and the gas lasers of continuous-wave carbon dioxide (CO_2), whose lasing medium is a mixture of carbon dioxide, nitrogen and helium. Power density of laser welding (10^9-10^{11} Wm^{-2}) is significantly higher than that of arc welding processes (10^6-10^8 Wm^{-2}), though somewhat lower than electron beam welding (10^{11}-10^{13} $Wm^{-2)}$ [3].

The beam energy delivered to the work-piece will be dissipated by reflection and absorption. Work-piece material is heated to a very high temperature, melted and may even vaporize due to very high power density concentrated in the focus of laser beam. Two modes of laser welding can be obtained, the heat conduction-mode and the deep-penetration mode, depending on the power density in use [22]. Heat conduction-mode is obtained for low power density, where most of the beam energy is lost by reflection (up to 90%), and it is characterized by the formation of a wide and shallow weld pool, see Figure 2.14 a). Power density is sufficient to melt the material but it is not enough to vaporize it, the weld pool shape being controlled by surface tension and thermocapillary forces [23]. This technique is used for welding small components for the electronics industry or for small medical parts.

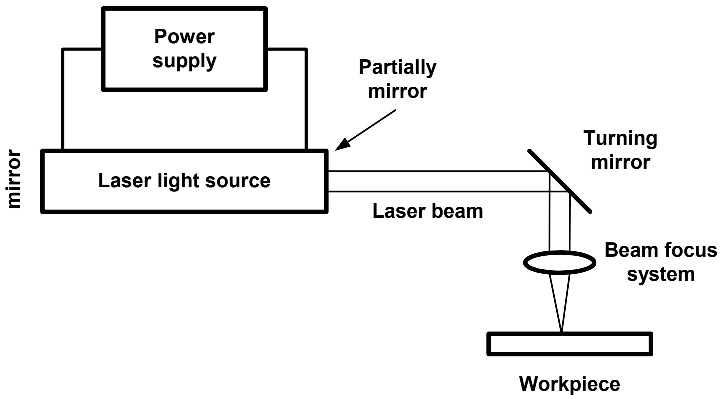

Figure 2.13. Schematic representation of a laser welding system

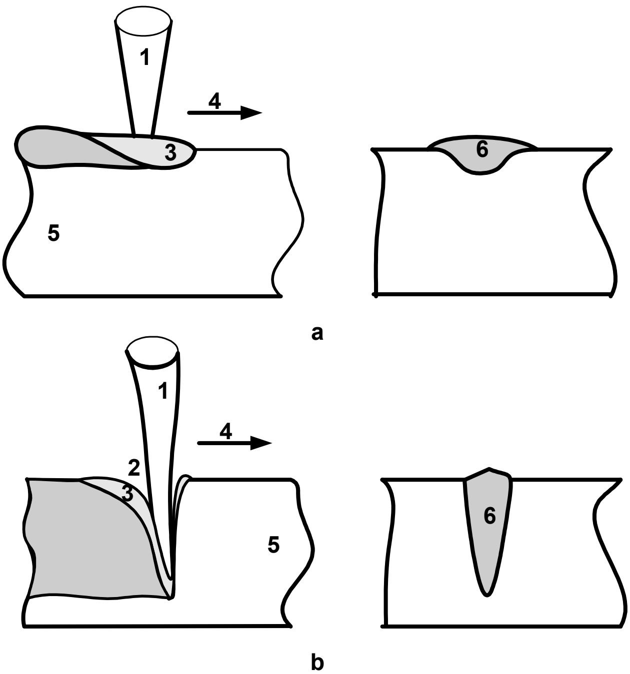

Figure 2.14. Laser welding modes: Heat conduction-mode – **a**; deep-penetration mode – **b**. Laser beam – 1; vapor channel – 2; weld pool – 3; welding direction – 4; work-piece – 5; solid melt – 6.

For power densities above a critical threshold of about 10^{10} Wm^{-2} the laser beam causes melting and vaporization of metal, creating a keyhole in the work-piece, as shown in Figure 2.14 b). The keyhole and plasma generated aid the adsorption of energy by the work-piece and the distribution of heat deep in the material. Metal vapor continuously generated tends to maintain the keyhole while metal flow and surface tension tend to obliterate it. As the laser beam advances it creates a channel and material solidifies behind it. This is the deep-penetration mode laser welding, which produces a narrow and deep welding seam. This welding mode is commonly applied for welding thick materials (up to 50 mm) at high travel speed [22], without filler metal, though filler electrodes can also be used to fill gaps.

The laser welding process provides a high energy density beam that can be used at room atmosphere to produce precise welds at high speed, even in difficult-to-weld materials, such as titanium. Added to this, welds are deep and narrow, with small heat affected zones, giving low distortion, and almost no post processing is necessary [29]. Main limitations of laser welding are the need for accurate part fit-up and precise part positioning as well as equipment capital cost that is ten times more expensive than arc welding systems of identical power. In addition the process is dependent on the material's light absorptivity and surface condition and it is susceptible to weld porosity, solidification cracking and bead geometric defects, mainly in aluminum alloys.

2.3.2 Welding Equipment

The welding equipment includes several types of lasers used in welding. In the following, solid-state lasers and gas lasers will be considered.

2.3.2.1 Solid-state Lasers

Solid-state lasers used in welding are of the ruby type, composed of a ruby crystal containing a concentration of 0.05% chromium, or of Nd:YAG type, made of a solid yttrium aluminum garnet rod doped with neodymium. Excitation of electrons in neodymium is done with high-power xenon flash lamps (1-4 kV), as represented schematically in Figure 2.15. This process is known as pumping. Diode lasers are frequently used as the pumping source instead of flash lamps, in order to improve pumping efficiency. Pumping energy is amplified within the crystal, commonly designated as cavity, which contains a fully reflecting mirror at one end and a partially reflecting mirror at the other. After amplification of radiation the laser beam is radiated from the partially reflecting end, with 1.064 μm wavelength. Because of the limited capacity of cooling systems to maintain a threshold temperature of the crystal Nd:YAG lasers are commercially available up to 6 kW average power, though conventional systems have generally up to 1000 W average power, with a maximum pulse power of 5 to 20 kW, a pulsing rate up to 400 pulses per second and a beam parameter of 25 (mm × mrad) or lower.

Commercial solid state lasers with high pulse power are capable of simultaneous welding at several different locations. The weld point diameter can also be adjusted by the processing optics at a constant working distance of 0.1 to 2 mm, and the welding depth can be controlled via the laser parameters up to 2 mm.

The Laser beam can also be transmitted through fiber optics which leads to several advantages, such as improved flexibility of laser systems and reduced need for accurate mirror alignment.

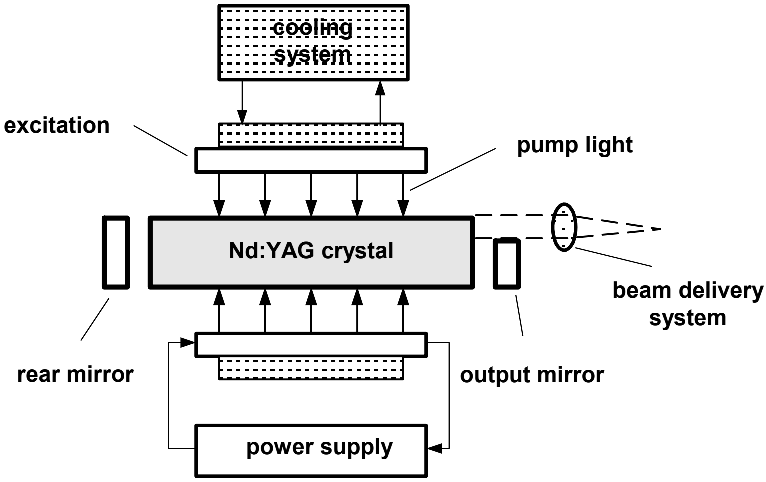

Figure 2.15. Schematic representation of a Nd:YAG laser system

2.3.2.2 Gas Lasers

Gas lasers have several characteristics different from solid lasers. The radiation wavelength of CO_2 lasers is 10.6 μm and the transmission of the laser beam is made by reflection using mirrors. They can be used in pulsed or continuous modes, in a power range up to 25 kW, though lower powers are more usual.

Axial flow CO_2 lasers are composed basically of a laser tube where the gas mixture flows, the front and rear mirrors and the radio frequency electrodes for excitation of the laser gas. The rear mirror is fully reflecting, opposite to the front mirror where a partially reflecting window exists. Windows of germanium or gallium arsenide are used in order to transmit laser beam without significant loss. The most usual laser gas mixtures are composed of carbon dioxide (5%), nitrogen (15%) and helium (80%) or oxygen (3.5%), carbon dioxide (4%), nitrogen (31.5%) and helium (61%). The gas mixture must be water cooled, because an increase in gas mixture temperature can cause decomposition of carbon dioxide and a decrease in efficiency of the laser. These lasers are called slow axial-flow lasers and are limited to small powers (500 W). In modern laser systems the heat generated in the gas is dissipated by the water-cooled electrodes (diffusion-cooled). A beam shaping module is integrated into the laser head and produces a high quality round symmetrical beam. The resonator design produces a 45° linearly polarized beam [29]. Output power up to 4.5 kW can be obtained with these lasers.

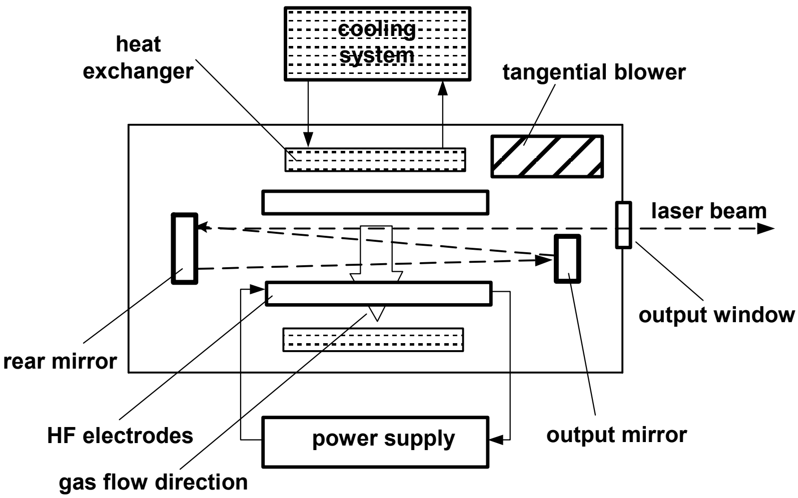

Figure 2.16. Schematic representation of a CO_2 transverse-flow laser system

In fast axial-flow lasers gas in the laser tube is re-circulated at high speed by blowers or turbines and heat removed by a heat exchanger. These lasers are composed of several optical units in series, in order to increase output power, with the optical resonator being folded several times to obtain a more compact system. The laser beam is transmitted between optical units by intermediate mirrors. Output powers up to 5 kW can be obtained with this type of laser.

In transverse-flow lasers gas is circulated into the discharge region transversely across the line of discharge by a tangential blower, being cooled by a heat exchanger, see Figure 2.16. This arrangement results in compact lasers, allowing shorter resonant cavities and higher outputs than axial-flow lasers. Power outputs up to 8 kW can be obtained with these lasers. Most of these lasers can be used with either continuous wave or pulsed wave, with variable pulse frequency between 0 and 100 kHz.

2.3.3 Process Parameters

Primary parameters of laser welding are the beam power, the beam diameter and travel speed, though other aspects, such as the control of plasma formation, the welding gases and the absorptivity of the parent material, can have drastic effect on weld penetration depth and on metallurgical changes in the weld.

2.3.3.1 Beam Power and Beam Diameter

Penetration depth increases almost linearly with increase of power density, for a specific diameter of the laser beam. Power density depends on the power of the laser beam and on the focus cross section area. Beam diameter is very small and it is difficult to evaluate because energy in the beam normally has a Gaussian distribution. This distribution is designated as the transverse electromagnetic $mode_{00}$ or TEM_{00}. Conventional definition of the beam diameter is based on the diameter where power density is $1/e^2$ of maximum power in central part. The circle defined in this way contains 86.5% of the total beam energy [3]. Other beam energy distributions may be observed, such as doughnut distributions, but they are not beneficial for welding operations because of the decrease of coherence of the beam.

2.3.3.2 Focus Characterization

Focus is basically characterized by the minimum focal spot size (d_{min}) and the focus depth (Z). Focal spot size is relevant to the determination of power density and its theoretical value can be determined by Equation 2.2, where f is the focal length of the focusing optics, λ is the wave length of the laser beam and D is the diameter of the unfocused beam, as illustrated in Figure 2.17. Frequently focused beam diameter is larger due to imperfections of the focusing optics [24].

$$d_{\min} = \frac{1.27 f\lambda}{D} \tag{2.2}$$

Focus depth is defined, according to *Laser Institute of America*, as the distance in which focus spot radius is increased by 5%. Focus depth can be estimated by Equation 2.3, where F equals $f\lambda$ of the optic system:

$$Z = 1.488 F^2 \lambda \tag{2.3}$$

Focus depth increases with increase of the F number of the focusing optics but focus diameter also increases, decreasing power density. Focus depth is important when welding thin components because thermal distortion can put beam focus out of these components.

The position of focus has great influence on quality of welds produced. If focus is well above the surface of the work-piece, welds show a nail head appearance and little penetration is obtained. When focus is positioned deep below the work-piece surface V-shaped welds result and a more accurate setting of the components is needed. Optimum focus positioning is below the work-piece surface but distance is a function of plate thickness and beam power.

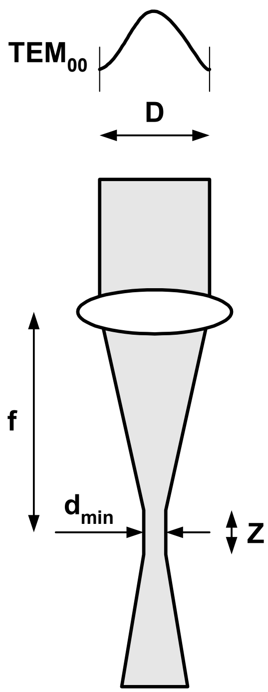

Figure 2.17. Characteristic parameters of focal system

2.3.3.3 Travel Speed

The increase of travel speed decreases penetration depth for both argon and helium shielding gases. This is because power input per unit length decreases with welding speed increase and keyhole may not be completely effective in trapping incident radiation. Very high speeds can give lack of fusion while low speeds may originate excessive parent material melt, vaporization and even defects formation. For very low speeds a reduction in penetration may be observed. This is attributed to the formation of a cloud of plasma, which attenuates the incident laser beam.

2.3.3.4 Plasma Formation

For power densities above 10^{10} Wm^{-2} in CO_2 lasers and 10^{12} Wm^{-2} in YAG lasers, the beam interacts with metal vapor and shielding gas, producing a cloud of plasma above the plate surface. During the initial moments of keyhole formation, plasma may assist the energy transfer to the work-piece. However, subsequently, plasma may limit beam energy transfer to the work-piece [25]. Several techniques have been developed to reduce plasma formation or to remove it from the weld zone. Pulsing laser power at high frequencies (above 1 kHz) is effective in reducing plasma formation in CO_2 lasers. In addition plasma is generally removed from the vicinity of the beam by an auxiliary jet of helium or argon. Assisting gas must be directed to 1 mm ahead of the beam, at an angle of approximately 20 degrees with the work-piece surface. Helium is preferred, because it has a higher ionization potential than argon, being more resistant to plasma formation. Beam interaction with the work-piece can also be improved by the combination of linear oscillation of the beam in welding direction with the jet of an inert gas [3].

2.3.3.5 Welding Gases

In laser welding two gases are commonly needed, the assisting gas to remove plasma, which is injected laterally, and a coaxial shielding gas to prevent atmospheric contamination. A root gas is also needed in keyhole welds where all the material thickness is melted. Helium and mixtures of argon and helium are used as welding gases. Argon shields the weld metal and helium is required to control the plasma formation in CO_2 laser welding. If Nd:YAGs are used for welding, the plasma formation is not an aspect of major concern and argon is the recommended welding gas. Small additions of oxygen, hydrogen or CO_2 can be used depending on material and process to increase productivity further [26]. Helium, argon or mixtures of these gases are used for most materials, including reactive metals such as titanium or zirconium. For reactive materials the shielded area must be increased, because they are sensitive to air contamination down to low temperatures (400 ºC). Nitrogen can also be used for welding stainless steels in less demanding applications [3].

2.3.3.6 Absorptivity

The efficiency of laser beam welding represents the proportion of beam energy that is effectively added to the work-piece. It is drastically affected by the absorptivity of the material to be welded. Absorptivity is a function of the electrical resistivity of the material, according to Equation 2.4, where A is the absorptivity and p_r the the electrical resistivity

$$A = 112.2\sqrt{p_r} \qquad 2.4$$

Absorptivity in many metallic materials is very low, 2 to 3% for aluminum or copper and less than 15% for stainless steel [22]. Absorptivity is increased by the formation of oxide layers in metallic materials. Absorbent powders can be applied in work-piece surface, in order to reduce reflection losses. The addition of active gases, such as oxygen, to shielding gas also improves absorptivity. In keyhole welding absorptivity suffers a large increase because of multiple reflections inside the keyhole, providing efficient welding even in high reflective materials such as aluminum [27].

The beam energy absorbed by a specific material is also a function of the radiation wavelength, generally increasing with the decrease of the wavelength. For steels absorptivity of Nd:YAG radiation is approximately three times of that of CO_2 laser radiation. For aluminum this difference is not so large and for other materials, such as copper or silver, no difference exists in this range of wavelength.

2.3.4 Process Variants

Dual beam laser welding has been proposed few years ago to improve fit-up tolerances and to reduce the probability of forming bead shape defects, such as humping and undercutting [59]. Beams can be mounted side-by-side or the second beam trails behind the primary beam.

Robotic hybrid welding processes were also developed to increase welding speed and deposition rate. This is the case for the combination of laser and GMAW processes. This combination provides high speed and good fit-up tolerance.

High power lasers, such as CO_2 lasers, needed for high speed welding of metals, require large floor space, considerable electrical and water services and regular maintenance. For precision welding applications, a new generation of lasers named diode lasers is available, providing a more efficient operation and maintenance-free running for more than 10000 h [28]. In fact it is not a variant but a new type of laser. These lasers incorporate diode chips, each one emitting a laser beam of very low power, when excited electrically. These chips are mounted into bars containing a cooling system and micro-channel lenses to focus individual laser beams. These bars have low power, around 60 W, and are mounted into diode stacks with other optical systems in order to obtain a focused laser beam with a power of several kW [29], as represented schematically in Figure 2.18. These lasers can be classified as low power diode lasers (LPDL), having power up to 150 W, and high power diode lasers (HPDL) with power ranging from 150 W to 4 kW. The lasers of this last group are used in welding operations. The wavelength of the laser beam is in the range 0.63 to 0.99 μm, though the interval 0.8 to 0.94 μm is common in welding applications. Aluminum has a marked increase of absorptivity in this wavelength range. Diode laser beam is not as coherent as Nd:YAG or CO_2 laser beams and focus is larger and rectangular instead of circular, being less sensitive for fitting of components to weld.

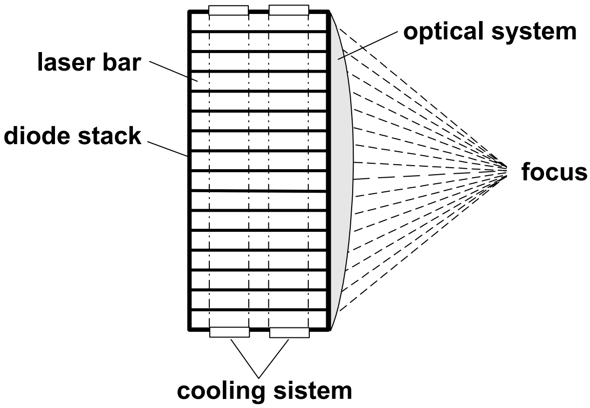

Figure 2.18. Schematic representation of a diode laser

This process has high energy efficiency (30-50%) when compared with CO_2 lasers (3-10%). Added to this, HPDL are compact and light and can be easily adapted to anthropomorphic robots with small pay-load (less than 25 kg). Running cost are approximately one-tenth of CO_2 lasers but beam quality is low [31]. HPDL are applied to the welding and brazing at high speed of carbon and stainless steels and aluminum alloys, as well as cladding operations. Thickness of welded components is limited by the power of the laser. They are becoming increasingly used in welding of thermoplastic materials, where they are replacing traditional techniques such as ultrasonic welding [32].

2.4 Resistance Spot Welding (RSW)

Resistance spot welding (RSW) is included in the group of resistance welding processes in which the heat is generated by passage of electric current through the bodies to be joined, according to Joule's law, expressed by Equation 2.5, where H is the heat generated, I is the current and t is the time of current flow:

$$H = I^2 Rt \qquad 2.5$$

Other welding processes such as resistance seam welding, projection welding, flash or upset welding and high-frequency welding are of the same group. Spot welding is the resistance welding process most widely used in robotic applications all over the world and is treated here with some detail. Main aspects of resistance seam welding process, which also has some relevance in industrial robotics, are analyzed in the section of process variants.

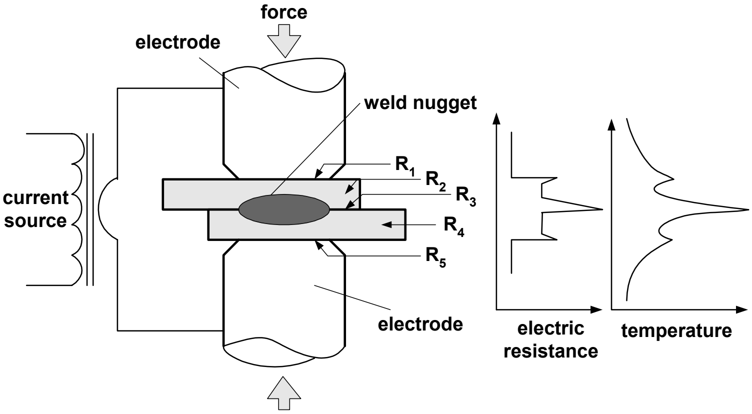

Figure 2.19. Schematic representation of the spot welding process. Electrode-work- piece interface resistances – R_1 and R_5; resistance of the work-pieces – R_2 and R_4; resistance in the interface between work-pieces – R_3

2.4.1 Introduction

In resistance spot welding overlapping sheets of metal are joined by applying electric current and pressure in the zone to weld with copper electrodes, as illustrated in Figure 2.19. Copper is used for electrodes because it has low electrical resistance and high thermal conductivity. Spot welding operation is composed of three steps that are the squeezing, welding and holding stages. Squeezing consists of applying the weld force to the work-pieces in order to obtain the appropriate amount of pressure, prior to welding. During welding, the electric current passes through the work-pieces, while the welding force is maintained, generating heat. In the course of the holding stage current is switched off and weld force maintained, allowing the weld to forge and cool under pressure.

The heat generated depends basically on the electrical current and time being used and on the electrical resistance of materials between electrodes. This inter-electrodes resistance is composed by five separated resistances, as is indicated in Figure 2.19. Resistances R_1 and R_5 are undesirable because they produce heating and consequently degradation of the electrodes. Resistances R_2 and R_4 are the resistances of the work-pieces and they assume particular importance in the final period of the weld. Low resistive materials are difficult to weld because of reduced heat generated in the pieces. Resistance R_3 is the most important because it determines nugget formation, assuring the establishment of the weld.

The nugget is a volume of melted material that forms in the interface of work-pieces with a diameter similar to that of the electrodes, as is indicated in Figure 2.19. Nugget penetration should be al least 20% of the thinnest sheet member but not exceeding 80% of the same thickness [31]. The passage of current initiates after the application of the electrodes force, leading the increase of temperature in the interface and developing a molten nugget. In the final part of the welding cycle plastic deformation occurs in the work-pieces, producing a visible and permanent indentation of the pieces. If current or pressure is too high, melted material can be expulsed (splashed) to the atmosphere.

The process has extensive application in welding of carbon steels because they have higher electrical resistivity and lower thermal conductivity than the electrodes made of copper. Aluminum alloys have an electrical resistivity and thermal conductivity that are closer to those of the copper, making difficult the welding operation of these materials, requiring higher levels of current, which can damage the electrode tips [32]. Other materials such as galvanized steels, heat-resisting alloys and reactive metals are also welded by this process. Since the process is very competitive it is widely used in automotive and aerospace industries as well in the manufacture of industrial and domestic equipment.

The major advantages of this process are the high welding speed and low thermal distortion, respectively faster and lower than in conventional arc welding processes, suitability for automation, the need of low skilled operators and the absence of joint preparation or filler metal. Some limitations of this process are the need for lap joints in thin materials, usually up to a thickness of 4 mm, the joints are not tight and have low tensile and fatigue strengths. Add to this fact that the initial equipment costs are higher than those of conventional arc welding equipment.

2.4.2 Welding Equipment

The main welding equipment to consider in resistance spot welding are the welding power sources and the electrodes. Those pieces of equipment will be considered next in detail.

2.4.2.1 Power Sources

Spot welding machines are composed basically an electrical circuit, which provides welding current, a control circuit that regulates welding current and welding time, and a mechanical system, used to apply welding force.

The electrical circuit consists of a step-down transformer, whose secondary circuit includes the electrodes and the work-pieces, see Figure 2.19. The transformer changes the input AC high-voltage and low amperage current, in the primary winding, to an AC high-amperage and low voltage current in the secondary winding. These transformers have low internal impedance, because current magnitude in secondary winding is inversely proportional to the impedance and depends directly on the open voltage of the secondary circuit.

Single-phase AC machines providing current up to 50 kA are widely used. Spot welders can also provide DC of continuous polarity, pulses of current of alternating polarity or pulsed mode [15]. Single or three-phase machines are available, though single-phase are commonly used because they are simpler to operate and have lower initial and maintenance costs for almost equivalent performance. Three types of direct current machines are generally available: the rectifier, the frequency converter and stored energy machines. The rectifier and frequency converter machines are fed from three-phase systems in contrast to stored energy machines that draw power from single-phase systems. These latter machines store energy during a period of time and then discharge a pulse of current to make the weld. These welders are useful for low frequency welds. Medium-frequency (400-2000) DC inverters are available for RSW. These inverters improve ability to control the welding process finely [60]. High-frequency DC inverters are being developed for further improvement of the process control.

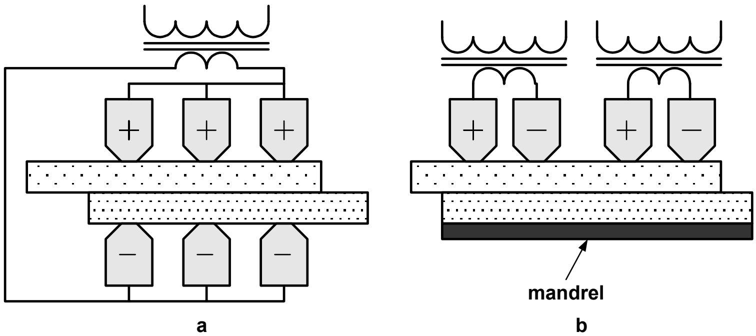

Figure 2.20. Arrangements of the secondary circuit for multiple spot welds; **a** - direct welding; **b** - series welding

In multiple spot welding the arrangement of the secondary circuit depends on whether they are direct or series welds, as is illustrated in Figure 2.20. In direct multiple-spot the welding conditions are similar in the three electrodes represented in Figure 2.20a; in series multiple-spot each of the two transformer secondary circuits shown in Figure 2.20 b makes two welds [33].

Most of the spot welders are computer controlled and allow the input of welding data. The simplest control sets current magnitude and welding time. More sophisticated controls allow to regulate current during welding as well provide and control preheat and post-heat operations [34].

Electrode clamping force is applied by hydraulic, pneumatic, magnetic or mechanical means, at a high controlled velocity in order prevent premature deformation of the electrodes. During the welding cycle, material clamped by the electrodes expands and contracts rapidly, because of the high heating and cooling rates, but working pressure must be maintained. When heated metal undergoes softening the electrodes must follow-up to maintain enough pressure on the sheet surfaces. If pressure drops during welding electrode-work-piece interface resistances increase, electrodes are overheated and may deteriorate. Clamping force can be variable during the cycle. Metals which have high shrinkage during solidification may need an increase of force to forge nugget after current passage. Modern systems allow control of the clamping force during all stages of the spot welding process. New portable gun units, incorporating the power transformer and the actuator into a common platform, facilitate the fitting of RSW to robotic systems.

2.4.2.2 Electrodes

Electrodes should have high electrical and thermal conductivities and must develop low electric contact resistance in order to prevent deterioration of the work-piece and electrodes. In addition they must have good strength to resist to deformation and wear at high temperature. They are made from copper containing alloy elements such as chromium (0.6-0.9%), cobalt (1-2%), beryllium (0.5%) and zirconium (0.08%). Electrodes are composed of three parts: the electrode cap or tip, the body of the electrode and the cooling system. Most of the electrodes are cylindrical with the tip machined to a truncated cone with an angle of 30º, though a variety of tip shapes (pointed, flat, dome and radius) is used to obtain access with complex joints. When welding thin sheets the electrode tip diameter (*d*) can be estimated by Equation 2.6, where t is the thickness of the sheet in contact with the electrode. For thicknesses above 1 mm electrode tip diameter is estimated by Equation 2.7:

$$d = \sqrt{t} \qquad \text{(a)} \qquad 2.6$$

$$d = 5\sqrt{t} \qquad \text{(b)} \qquad 2.7$$

When welding sheets of dissimilar thicknesses the electrode diameter should be specified for the thinner material. The weld diameter (*D*) should be similar to the electrode diameter. Repeated heating and cooling of the electrode and pick-up of metal particles causes electrode tip deterioration. Maximum tip diameter allowed is 1.3 times the initial diameter. When the electrode tip reaches this diameter it should be replaced or redressed to the original diameter.

Electrodes should be water cooled at a flow rate above 4 l/min and separate water circuits must be used for both top and bottom electrodes.

2.4.3 Process Parameters

According to Joule's law the welding parameters are current, time and electric resistance. Electric resistance is a function of several parameters such as electric resistivity of materials, surface quality of sheet metal and clamping force. Electric resistivity is a characteristic of the materials and varies with temperature during welding. Material surface quality depends on roughness and cleanliness of the surfaces of sheet materials. Parameters that can be programmed in the welding machine are current, time and welding force. The choice of welding conditions depends on thickness and physical properties of metals being welded and even on the type of the welding equipment.

2.4.3.1 Welding Current and Time

Heat developed during welding is proportional to time and to square of current. Though both parameters are responsible for heat generation, the weld heating rate is determined only by current, because heat lost to the work-piece and to copper electrodes increases with weld time. Heat lost to the work-piece increases heat affected zone and thermal distortion, while heat in the electrodes can degradate them, all being undesirable effects. The level of current required for any metal tends to be inversely proportional to its electrical and thermal resistivities.

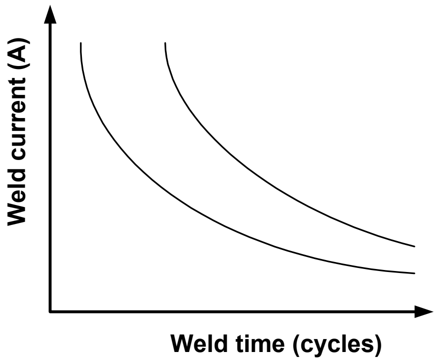

Figure 2.21. Schematic representation of current-time relationship for RSW

The size of the weld nugget increases rapidly with increasing current. When welding a particular material and thickness, if current is increased welding time should be decreased, see Figure 2.21, in order to prevent high surface indentation or even expulsion of melted material and deterioration of electrodes [35]. The expulsion of material defines the upper limit of usable current.

Welding currents range from 20 to 100 kA, mainly for light alloys, though the most usual are between 4 and 20 kA for carbon steels. Time is defined in cycles of 50 Hz supply and it is between 5 and 100 Hz for steels and 5 and 20 Hz for light alloys, in sheets up to 3 mm thick.

Weld current cycles may have different shapes that depend on the materials being welded, as shown in Figure 2.22. A cycle of constant current magnitude, Figure 2.22a, represents the simplest situation and is suitable for welding mild steels. For high strength steels sensitive to cold cracking a modulated welding current with a rise time t_r and a fall time t_f, see Figure 2.22b, can be used to allow gradual heating and cooling of the weld. In the case of materials prone to form brittle structures in the weld an additional current cycle of magnitude I_a, see Figure 2.22c, can be useful to anneal the weld. In spot welding of thick materials (over 3 mm) the use of several pulses of current, Figure 2.22d, is effective.

2.4.3.2 Welding Force

The increase of the welding force reduces contact resistance because, in first analysis, it promotes the increase of contact area, due to deformation of surface asperities and eventually the rupture of surface oxide films [36]. Electrode clamping forces must be high, particularly when welding low resistivity metals in order to reduce the proportion of heat generated in the interface electrode/work-piece. Electrode force must be increased with increasing current, unless part of the melted material of the nugget can be expelled. Other factors such as bad fit and lack of mechanical support contributes for the material expulsion. Distance of the weld to the edge of the sheets should be larger than 1.5 *D*, where *D* is the weld diameter. Excessively high forces are also undesirable because they can cause large surface indentation of the work-pieces and damage of the electrodes.

Electrode clamping force increases with increasing thickness and strength of the work-pieces. Forces between 1000 and 15,000 N are usual for plate thicknesses up to 3 mm, though values of 20,000 N can be used in steel sheets 6 mm thick.

Clamping force starts before the passage of current initiates and is maintained after the current is cut off, as is illustrated in Figure 2.22. Sometimes an increase of force is applied after current passage to forge the weld, see Figure 2.22b.

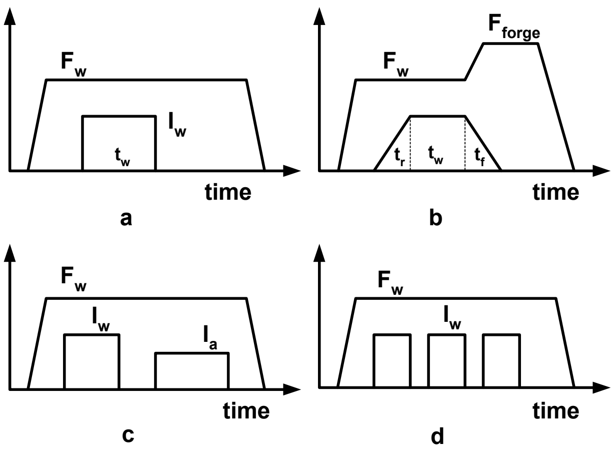

Figure 2.22. Timing diagrams of current and force for spot welding: Welding current – I_w; welding time – t_w; rise time – t_r; fall time – t_f; welding force – F_w; forge force – F_{forge}; annealing current

2.4.4 Process Variants

Resistance seam welding (RSEW) is used when a continuous seam is required. This seam consists of a series of overlap spot welds, as shown in Figure 2.23. This process is similar to resistance spot welding, but the electrodes are replaced by power driven wheels or rollers that move along the joint. Electric current passes intermittently while the wheels are stationary, without the necessity of raising or lowering the welding head. The amount of overlap between spots is 25-50%. The process can be used to do spot welds by simple adjustment of timing. The weld width in continuous welds is between $2\sqrt{t}$ and $5\sqrt{t}$, where t is the single sheet thickness. The track tends to deform due to continuous work and a device is needed to correct the shape of the wheel edge.

RSEW machines can be of circular type, where the axis of rotation of the electrode wheel is at right angles to the front of the machine, of longitudinal type, where the the axis of rotation of the electrode wheel is parallel to the front of the machine, and of universal type, which allows the orientation of the axis of rotation of the electrode wheels to be changed [32]. Portable machines are also available for welding large work-pieces that are difficult to handle by conventional equipment.

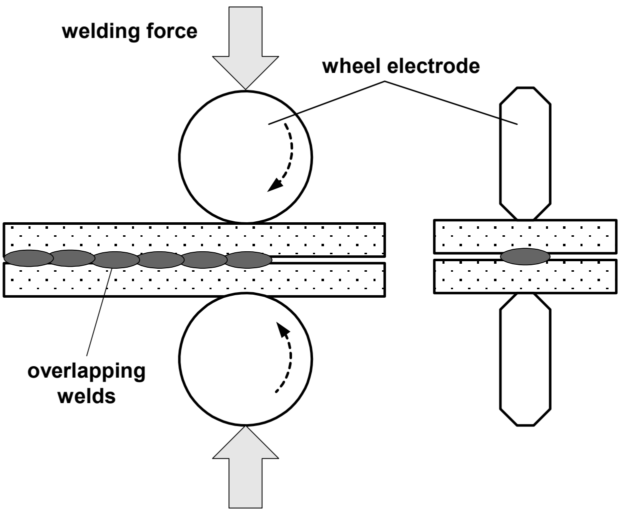

Figure 2.23. Seam welding principle

Electrode wheels are made of the same materials of RSW electrodes, with diameters between 50 and 610 mm and can have internal or external cooling. Internal cooling may have higher operational costs and do not cool the weld.

Maximum welding current in conventional RSEW machines ranges commonly from 20 to 30 kA, though welders up to 100 kA are applied in welding of light alloys. Clamping forces between 2000 and 16000 N and welding speeds ranging from 1 to 12 m/min are used for steels, though lower values of force and speed are applied in aluminum alloys.

Carbon, low-alloy, stainless and coated steels are currently welded using this process. Welding of light alloys requires additional precautions because of their lower electrical resistivity and lower melting temperature. A new process named conductive heat resistance seam welding allows one to increase the welding speed and reduce joint preparation cost in difficult-to-weld aluminum alloys [37].

RSEW is largely used in the automotive industry as well as in manufacturing of heat exchangers, non-pressurized tanks and several types of cans.

Main advantages of this process when compared with resistance spot welding are the capacity to produce gas-tight and liquid-tight welds as well as the possibility of reduction of the overlap width of the sheets. However, the weld must progress in a straight line or in a uniformly curved line of large radius and thermal distortion can be higher than in resistance spot welding.

This process has several variants such as mash-seam welding, butt seam welding, high frequency resistance welding and high frequency induction welding [38] but they are outside the scope of this introduction.

2.5 Friction Stir Welding (FSW)

Friction stir welding (FSW) is a solid state joining process invented at *The Welding Institute (TWI)* in 1991 [39], in which a non-consumable rotating tool is slowly plunged into the butting faces of the work-pieces and traversed along the joint line, see Figure 2.24a. Pieces to be welded have to be clamped in order to prevent joint faces from being moved out of position.

Heat is generated by tool friction, under the tool shoulder and on the probe surface, and by plastic deformation of the material [40]. Heat generated is lost to the work-pieces, to the tool and to the anvil, as represented schematically in Figure 2.24b. Maximum temperatures are attained close the tool shoulder and are lower than the melting temperature of the materials being welded [41], though incipient melting has been reported for some materials. Heat produced creates a softened plasticized region around the tool, which facilitates the movement of the tool along the joint line. Plasticized material is chaotic mixed or extruded from the advancing side to the retreating side of the tool [42],[43] and it is forged by the contact of the tool shoulder and of the pin, producing a solid phase bond between the two pieces.

2.5.1 Introduction

This welding process leads to the appearance of a thermo-mechanically affected zone (TMAZ), which results from both plastic deformation and thermal exposure of the material, and of a heat affected zone (HAZ), which only suffers the effect of the thermal cycle. In the central part of the TMAZ there usually appears a distinct nugget, having an onion ring feature, attributed to dynamic re-crystallization or dynamic recovery of the microstructure [44].

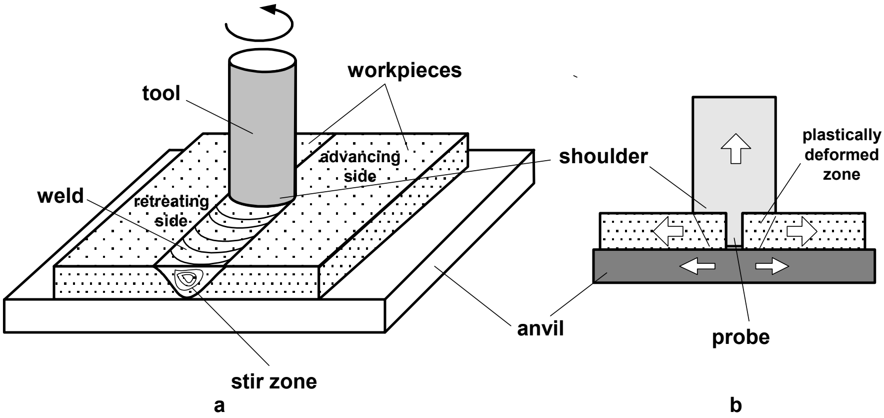

Figure 2.24. Schematic representation of the friction stir welding process

FSW is mainly used in welding of aluminum alloys, though other materials such as magnesium, copper, zinc, titanium and even steel [44] can be welded with this process. This process can be used too for welding aluminum alloys of different alloy groups or yet dissimilar materials, metal matrix composites and plastics. It presents several advantages when compared with conventional arc welding processes, mainly in the welding of aluminum alloys. Difficulties related to sensitivity to solidification cracking, gas porosity caused by the hydrogen absorbed during welding and thermal distortion, very common in fusion welding processes, do not happen in this process. Other benefits of the process include good strength and ductility along with minimization of residual stress and distortion. These qualities of FSW are generally attributed to the solid-state nature of the process and a supposed low energy input to the welded joint. In addition to this no filler electrode, no shielding gas and minimum surface preparation is needed. No environmental concerns have to be considered because neither fumes nor toxic gases nor radiation of the electric arc are produced in this process.

However, there are still several drawbacks that need to be addressed in order to facilitate industrial application of this process. The system requires high forces to move the tool through the plasticized material, which in turn wears the tool, mainly in welding of hard materials. Powerful clamping fixtures are also needed to hold pieces down and counteract forging forces from the tool. Because of this, FSW is usually carried out in custom heavy-duty machine tool equipment, where weld joints are frequently limited to straight lines or two-dimensional contours. The use of industrial robots increases the flexibility of this process, providing the ability to weld three-dimensional contours [46].

Nowadays FSW is used in the welding of pieces in aluminum alloys ranging in thickness from 0.5 to 75 mm. It is being used in the shipbuilding and the marine industries, for manufacturing of panels, platforms and heavy profiles, in the aerospace industry for production of fuel tanks, wings and fuselages, in the railway industry for high speed trains, in the automotive industry, for production of panels and other components, *etc.*

2.5.2 Welding Equipment

In the beginning mainly high stiffness machines were developed, specifically tailored to meet client needs, but nowadays standardized, flexible and modular systems suited to several industry segments are being produced too, for welding nonferrous metals. These latter systems consist of a sturdy basic framework, a set of safety stops, a welding carriage assembly, a welding head assembly, a control system, a hydraulic unit and the welding tools [47]. These machines can have several basic designs, providing vertical down forces ranging from 6 to 200 kN, welding speeds up to 2 m/min, though an option up to 6 m/min exists, and tool rotation speed between 500 and 2000 rpm.

As referred above these machines have low flexibility producing welds in simple two or three-dimensional pathways. Robotic systems allow the improving of flexibility but need to be able to apply and maintain a large and constant axial force during the welding operation, which is not simple in these systems. This is done using high payload robots that sense the force directly and use feedback to maintain the force during the welding operation. The axial force decreases with increasing tool rotation speed but increases with increasing travel speed, and therefore for robotic FSW a compromise may need to be established between travel speed and axial force requirements [46].

The appropriate tool type is a key factor of the quality of friction stir welded joints. For butt welding aluminum alloys of thickness up to 12 mm cylindrical threaded pin probes are recommended, while for thicker plates the Whorl and MX-Triflute probes should be used [48], see Figure 2.25. These latter probe types allow welding speeds that exceed largely those achievable with threaded pin probes: at least by a factor of 2. In addition they have flat or re-entrant features or oval cross section, which reduce the probe volume (static volume), allowing one to achieve a suitable swept volume (dynamic volume) to static volume ratio. The greater this ratio, the greater the path for material flow and the efficiency of the probe [49].

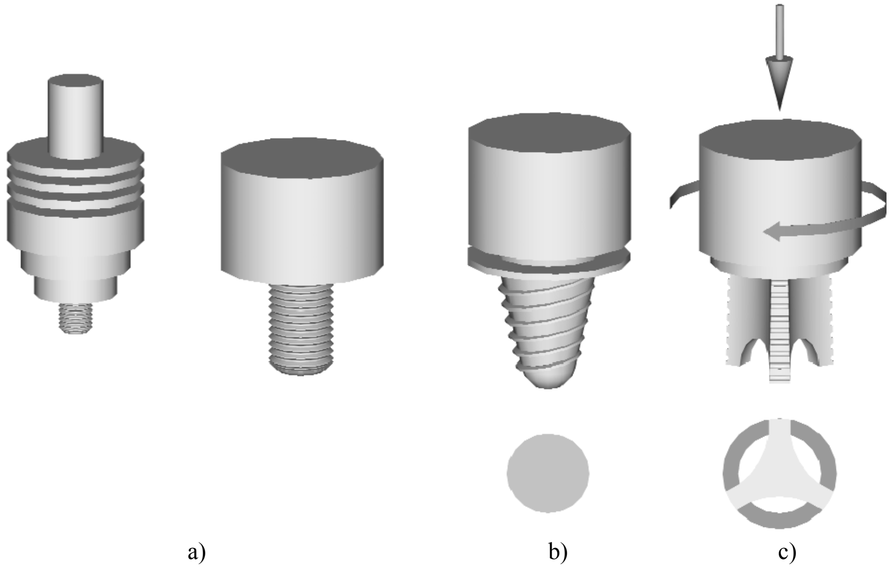

Figure 2.25. Friction stir welding probes. Cylindrical threaded pin probe – **a**; oval shape Whorl probe - **b**; flared-triflute probe – **c**

For lap welding of aluminum alloys, which is more difficult than butt welding because wider welds are necessary and oxide disruption at the sheet interface is more difficult, special tools are used, such as Flared-Triflute and A-Skew probes [49]. These tools allow the dynamic to static volume ratio to be increased, improving weld quality.

The shape of the bottom of the tool shoulder affects material flow around the probe and contributes to preventing the escape of plasticized material. They can be flat or concave, smooth or grooved, with concentric or spiral grooves [50]. A concave shoulder bottom has the advantage, when compared with a flat bottom, of directing material flow to the center close the probe. Grooved bottoms have in general the same effect. Shoulders can also have knives to shave the weld.

In general this welding process requires access to both sides of the work-pieces being welded, although by using a special tool (bobin-tool) it is possible to do the welds without the need for an anvil [51].

2.5.3 Process Parameters

The main parameters of the FSW process, which are determinant for the quality of the welded joint, are the vertical down force, also designated tool plunge force, the tool rotation speed and the travel speed or welding speed. Plunge force assures penetration of the probe into the plates and forges plasticized material under the shoulder. The tool rotation speed directly influences the heat generated in the process because the mechanical power input to the tool is given by Equation 2.8, where P is the power, M the torque and Ω is the angular speed of the tool.

$$P = M\Omega \qquad 2.8$$

The mechanical power input is dissipated mainly by thermal losses because plastic work may be neglected. Heat generated in the process is also influenced by the plunge force because it affects the torque. Heat generated increases with increasing tool rotation speed and tool plunge force. Travel speed influences the heat input per unit weld length (specific heat input), affecting metal flow around the probe. Specific heat input decreases with increasing travel speed, which reduces material softening in the vicinity of the probe, making plastic flow more difficult. High travel speeds may cause defects, such as cavities. For low tool rotation speed, low plunge force and high travel speed external defects may form for welds in some aluminum alloys. The increase of the plunge force moves defects to the interior of the weld [52]. The ratio tool rotation speed *vs* travel speed is sometimes used to distinguish between hot welds, having high ratio, and cold welds, with low ratio. Hot welds are less sensitive to defect formation but may exhibit more significant changes in microstructure and mechanical properties than cold welds in aluminum alloys.

Other relevant parameters are the time of indentation of the tool and the tool shoulder angle, besides the other geometric characteristics of the tool referred in the previous section. The time of indentation of the tool is the period between the instant the tool contacts the work-piece and the instant the tool begins moving along the joint. During this period generated heat spreads in the vicinity of the probe, softening material and stabilizing material flow around the probe. If this period is too short defects can appear in the initial part of the weld. Time can range usually from 5 to 30 s. The tool shoulder angle allows a gradual increase of the pressure on the top surface of the plates being welded and helps to direct the material flow. Tool angles up to 3° are common.

2.5.4 Process Variants

In the last few years several variants of FSW process have been developed. One of these variants is thermal assisted FSW in which a heat source is applied in the joint before the FSW tool, in order to preheat and soften the material [53]. This reduces welding forces, welding power and tool wear and increases travel speed. This variant can be useful in welding of steels and other high strength materials.

Another variant is spot FSW, developed for lap joints, that produces spot welds having higher mechanical strength than those produced by resistance spot welding. Robotic applications of this process are being developed [54].

A recent development is the reversal stir welding process (Re-Stir™), developed by TWI, in which tool rotation is applied as both angular reciprocating, where reversal is imposed within one revolution, and rotary reversal, where reversal is imposed after one or more revolutions, instead of continuous rotation as is in conventional FSW. Re-Stir is basically a cyclic and essentially symmetrical process. According to TWI Re-stir™ may become the preferred option for certain butt, lap, compound lap and spot welding and material processing applications [55].

2.6 Health and Safety

The major potential hazards of arc welding processes are the high-voltage electricity, which can injure and kill personnel, the fumes and gases, which can be dangerous to health, the electric arc radiation, which can injure eyes and burn skin and the noise that can damage hearing.

The exposure to the high open-circuit voltage of power supplies can cause dangerous electric shocks, which can be prevented by connecting all the electrical equipment and work-pieces to a suitable electrical ground. All electric cables should be suited to the maximum current and must remain insulated and dry.

Fumes and gases are generated in all arc welding processes, being particularly intense in the flux cored arc welding process. Metal fumes of nickel, chromium, zinc, lead or cadmium, for example, and gases such as carbon monoxide, ozone and nitrogen oxides formed in the arc are very harmful to the health [56]. Enough ventilation or exhaust at the arc, or both must be used in order to keep fumes and gases from the personnel breathing zone.

The electric arc of GTAW and GMAW processes emits intense radiation in the ultraviolet range, in the infrared range and also in the visible range. UV radiation can commonly cause a temporary eye burn, which can be painful for 48 h. A filter glass should be used by the operator to absorb the radiation in the dangerous wavelengths, and limit visible light so he can see the joint during the welding operation. There are two basic types of filter, permanent filters and photosensitive filters, which react rapidly to the incident light from the arc and darken [55]. Optical density of filters increases with increasing current. The UV also occasions reddening and irritation of the skin and operators need to be protected by leather, wool or aluminum coated clothing. Robotic welding systems are generally protected by enclosures provided with windows with filters for viewing weld area.

Ear protection should be used when noise is excessive in the work area. Special care must be taken in handling and use of cylinders containing high-pressure and liquefied gases, which should remain in a vertical position, secured with chains, when they are being used.

Lubricants or other flammable compounds should not be used in pressure-reducing regulators and other parts of the oxygen circuit because they can lead to catastrophic fire.

Potential hazards in laser beam welding are in many aspects similar to those observed in arc welding. Laser power supplies employ high voltage capable of producing lethal electric shocks. Laser welding also generates dangerous metal fumes, whose composition depends on the metals being welded, requiring local exhaust ventilation. However laser beams can cause permanent eye damage, so exposure to direct or reflected laser beams must be prevented. Laser welding systems must operate in restricted access enclosures opaque to the laser wavelength. Individual laser eye protection can be required for personnel working in the vicinity of the laser source [22]. Thermal burns can also occur if skin is exposed to primary laser beams.

Principal motives of concern in resistance spot welding are protection against molten metal spatter and splash and electric shock. Working environment can be improved by the use of enclosures and splash-less resistance spot welding systems [57].

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