59. Welding Automation

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This Chapter focuses on automation of welding processes that are commonly used in industry for joining metals, thermoplastics, and composite materials. It includes a brief review of the most important welding techniques, welding equipment and power sources, sensors, manipulating devices, and controllers. Particular emphasis is given to monitoring and control strategies, seam-tracking methods, integration of welding equipment with robotic manipulators, computer-based control architectures, and offline programming of robotic welding systems. Application examples demonstrating state-of-the-art and recent advances in robot-based welding are also presented. Conclusions define next challenges and future trends in enhancing of welding technology and its automation potential, modeling and control of welding processes, development of welding equipment and dedicated robotic manipulators, automation of robot programming and process planning, human–machine interfaces, and integration of the automated robotic stations within the global production system.

59.1 Principal Definitions

Welding is a manufacturing process by which two pieces of materials (metals or thermoplastics) are joined together through coalescence. This is usually achieved by melting the workpieces and adding a filler material that causes the coalescence and, after cooling, forms a strong joint. Sometimes, pressure is applied in combination with heat, or alone. At present, heat welding is the most common welding process, which is widely used in automotive, aerospace, shipbuilding, chemical and petroleum industries, power generating, manufacturing of machinery, and other areas [59.1–3].

For heat welding, many different energy sources can be used, including a gas flame, an electric arc, a laser or an electron beam, friction, etc. Depending on the mode of energy transfer, the American Welding Society (AWS) has grouped welding/joining processes and assigned them official letter designations, which are used for identification on drawings and in technological documentation. In particular, the AWS distinguishes arc welding, gas welding, resistance welding, solid-state welding, and other welding processes. Within each group, processes are distinguished depending on the influence of capillary attraction (which is the ability of
a substance to draw another substance into it). For instance, the arc welding group includes gas metal arc (GMAW), gas tungsten arc (GTAW), flux cored arc welding (FCAW), and other types of welding. Detailed and complete classification of the welding processes is given in [59.4].

59.2 Welding Processes

59.2.1 Arc Welding

This group uses an electric arc between an electrode and the base material in order to melt metals at the welding point. The arc is created by direct or alternating current using consumable or nonconsumable electrodes. The welding region may also be protected from atmospheric oxidation and contamination by an inert or semi-inert gas (shielding gas). The oldest process of this type, carbon arc welding (CAW), uses a carbon electrode and has limited applications today. It has been replaced by metal arc welding. A typical example is shielded metal arc welding (SMAW), in which a flux-covered metal electrode produces both shielding (CO₂ from decomposition of the covering) and filler metal (from melting of the electrode core). This process is widely used in manual welding and is rather slow, since the consumable electrode rods (or sticks) must be frequently replaced.

Automatic arc welding is mainly based on the gas metal arc welding (GMAW) process, also known as metal inert gas (MIG) or metal active gas (MAG) welding [59.5]. The process uses a continuous wire feed as a consumable electrode and an inert or semi-inert gas mixture as shielding (Fig. 59.1a). The wire electrode is fed from a spool, through a welding torch. Since the electrode is continuous, this process is faster compared than SMAW. Besides, the smaller arc size allows making overhead joints. However, the GMAW equipment is more complex and expensive, and requires more complex setup. During operation, the process is controlled with respect to arc length and wire feeding speed. GMAW is the most common welding process in industry today; it is suitable for all thicknesses of steels,

![Fig. 59.1a–d Schematics of typical arc welding processes: (after [59.4])](image-url)
aluminum, nickel, stainless steels, etc. This process has many variations depending on the type of welded metal and shielding gas, and also the metal transfer mode.

A related process, flux-cored arc welding (FCAW), uses similar equipment but is based on a continuously fed flux-filled electrode, which consists of a tubular steel wire containing flux (a substance which facilitates welding by chemically cleaning the metals to be joined) at its core (Fig. 59.1b). The heat of the arc decomposes the electrode core producing gas for shielding and also deoxidizers, ionizers, and purifying agents. Additional shielding may be obtained from externally supplied gas. Obviously, this cored wire is more expensive than the standard solid one, but it enables higher welding speed and greater metal penetration.

Another variation is submerged arc welding (SAW) that is also based on the consumable continuously fed electrode (solid or flux cored), but the arc zone is protected by being submerged under a covering layer of granular fusible flux. When molten, the flux generates protective gases and provides a current path between the electrode and the base metal. Besides, the flux creates a glass-like slag, which is lighter than the deposited metal from the electrode, so the flux floats on the surface as a protective cover. This increases arc quality, since atmospheric contaminants are blocked by the flux. Also, working conditions are much better because the flux hides the arc, eliminating visible arc light, sparks, smoke, and spatters. However, prior to welding, a thin layer of flux powder must be placed on the welding surfaces.

For nonferrous materials (such as aluminum, magnesium, and copper alloys) and thin sections of stainless steel, welding is performed by the gas tungsten arc welding (GTAW) process, also referred to as tungsten inert gas (TIG) welding. The process uses a nonconsumable tungsten electrode with high melting temperature, so the arc heat causes melting of the workpiece and additional filling wire only (Fig. 59.1c). As an option, the filling metal may not be used (autogenous welding). The weld area is protected from air contamination by a stream of inert gas, usually helium or argon, which is fed through the torch. Because of the smaller heat zone and weld puddle, GTAW yields better quality compared with other arc welding techniques, but is usually slower. The process also allows a precise control, since heat input does not depend on the filler material rate. Another advantage is the wide range of materials that can be welded, so this process is widely used in the airspace, chemical, and nuclear power industries.

A related process, plasma arc welding (PAW), uses a slightly different welding torch to produce a more focused welding arc. In this technique, which is also based on a nonconsumable electrode, an electric arc transforms an inert gas into plasma (i.e., an electrically conductive ionized gas of extremely high temperature) that provides a current path between the electrode and the workpiece (Fig. 59.1d). Similar to the GTAW process, the workpiece is melted by the intense heat of the arc, but very high power concentration is achieved. To initiate the plasma arc, a tungsten electrode is located within a copper nozzle. First, a pilot arc is initiated between the nozzle and the workpiece, then it is transferred to the workpiece. Shielding is obtained from the hot ionized gas (normally argon) issuing from the orifice. In addition, a secondary gas is used (argon, argon/hydrogen or helium), which assists in shielding. PAW is characterized by extremely high temperatures (30000 °F), which enables very high welding speeds and exceptionally high-quality welds; it can be used for welding of most commercial metals of various thicknesses. A variation of PAW is plasma cutting, an efficient steel cutting process.

59.2.2 Resistance Welding

Resistance welding is a group of welding processes in which the heat is generated by high electrical current passing through the contact between two or more metal surfaces under the pressure of copper electrodes. Small pools of molten metal are formed at the contact area, which possess the highest electrical resistance in this circuit. In general, these methods are efficient and produce little pollution, but their applications are limited to relatively thin materials. There are several processes of this type; two of them are briefly described below.

Resistance spot welding (RSW) is used to join overlapping thin metal sheets, typically, of 0.5–3.0 mm thickness. It employs two nonconsumable copper alloy electrodes to apply pressure and deliver current to the welding area (Fig. 59.2a). The electrodes clamp the metal sheets together, creating a temporary electrical circuit through them. This results in rapid heating of the contact area to the melting point, which is transformed into a nugget of welded metal after the current is removed. The amount of heat released in the spot is determined by the amplitude and duration of the current, which are adjusted to match the material and the sheet thickness. The size and shape of the spots also depend on the size and contour of the electrodes. The main advantages of this method are efficient energy use,
low workpiece deformation, no filler materials, and no requirements for the welding position. Besides, this process allows high production rates and easy automation. However, the weld strength is significantly lower than for other methods, making RSW suitable for certain applications only (it is widely used in the automotive industry where cars can have up to several thousand spot welds).

**Resistance seam welding (RSEW)** is a modification of spot welding where the bar-shaped electrodes are replaced by rotating copper wheels. The rotating electrodes are moved along the weld line (or vice versa, the workpiece is moved between the electrodes), progressively applying pressure and creating an electrical circuit (Fig. 59.2b). This allows obtaining long continuous welds (for direct current) or series of overlapping spot welds (for alternative or pulsed current). In seam welding, more complicated control is required, involving coordination of the travel speed, applied pressure, and electrical current to provide the overlapping welds. This process may be automated and is quite common for making flange welds, watertight joints for tanks, and metal containers such as beverage cans. There are a number of process variants for specific applications, which include wide wheel seam, narrow wheel seam, consumable wire seam welding, and others.

### 59.2.3 High-Energy Beam Welding

Energy beam welding is a relatively new technology that has become popular in industry due to its high precision and quality [59.6]. It includes two main processes, laser beam welding and electron beam welding, differing mainly in the source of energy delivered to the welding area. Both processes are very fast, allow for automation, and are attractive for high-volume production.

**Laser beam welding (LBW)** uses a concentrated coherent light as the heat source to melt metals to be welded. Due to the extremely high energy concentration, it produces very narrow and deep-penetration welds with minimum heat-effective zones. Welds may be fabricated with or without filler metal; the molten pool is protected by an externally supplied shielding gas. It is a versatile process, capable of welding most commercially important metals, including steel, stainless steel, titanium, nickel, copper, and certain dissimilar metal combinations with a wide range of thickness. By using special optical lenses and mirrors, the laser beam can be directed, shaped, and focused on the workpiece surface with great accuracy. Since the light can be transmitted through the air, there is no need for vacuum, which simplifies equipment and lowers operating cost. The beam is usually generated using a gas-based CO₂ solid-state Nd:yttrium–aluminum–garnet (YAG) or semiconductor-based diode lasers, which can operate in pulsed or continuous mode. Furthermore, the beam is delivered to the weld area through fiber optics. For welding, the beam energy is maintained below the vaporization temperature of the workpiece material (higher energy is used for hole drilling or cutting where vaporization is required). Advantages of LBW include high welding speed, high mechanical properties, low distortion, and no slag or spatter. The process is commonly used in the automotive industry.

A derivative of LBW, dual laser beam welding, uses two equal power beams obtained by splitting the original one. This leads to a further increase in welding speed and improvement of cooling conditions. Another variation, laser hybrid welding, combines the laser with metal arc welding. This combination also offers advantages, since GMAW supplies molten metal to fill the joint, and a laser increases the welding speed. Weld quality is higher as well, as the potential for undercutting is reduced.

**Electron beam welding (EBW)** is a welding process in which the heat is obtained from high-velocity electrons bombarding the surfaces to be joined. The electrons are accelerated to a very high velocity (about
50% of the speed of light), so beam penetration is extremely high and the heat-affected zone is small, allowing joining of almost all metals and their combinations. To achieve such a high electron speed and to prevent dispersion, the beam is always generated in high vacuum and then delivered to the workpiece located in a chamber with medium vacuum or even out of vacuum. In the last case, specially designed orifices separate a series of chambers at various vacuum levels. Because of the vacuum, a shielding gas is not used, while a filler metal may be used for some materials (for deoxidizing the melted plain carbon steel that emits gases, to prevent weld porosity). The EBW process provides very narrow and high-quality welds; it is commonly used for joining stainless steels, superalloys, and reactive and refractory metals. The primary disadvantage of the EBW is high equipment cost and high operation price (due to the need for vacuum). Besides, location of the parts with respect to the beam must be very accurate.

59.3 Basic Equipment and Control Parameters

The described welding technologies utilize various types of equipment and control units. However, since arc and resistance spot welding are used in manufacturing most widely, they are expanded upon in more detail.

59.3.1 Arc Welding Equipment

Arc-welding processes employ the basic electrical circuit, where the currents typically vary from 100 to 1000 A, and voltage ranges from 10 to 50 V. The power supply can produce either direct current (DC) or alternating current (AC), and usually can maintain either constant current or constant voltage. Consumable-electrode processes (such as GMAW) generally use direct current, while nonconsumable-electrode processes (GTAW, etc.) can use either direct current (with negative electrode polarity) or alternating current (with square-wave AC pattern) [59.1, 3, 5].

For arc welding processes, the voltage is directly related to the arc length, and the current is related to the amount of heat produced. So, constant-current power supplies are most often used for manual welding, because they maintain a relatively constant heat output even if the voltage varies due to imperfect control of electrode position. Constant-voltage power supplies are usually utilized for automated welding, since the electrode spatial position (and arc length) is properly controlled and the current sensor can be used for adjusting the electrode position in the feedback loop.

Typical welding equipment for the GMAW process is shown in Fig. 59.3. It includes a power supply, welding cables, a welding gun, a water cooling unit, a shielding gas supplier, wire feed system, and a process control unit. Here, the cathode (negative) cable is connected to the workpiece, and the anode (positive) cable is connected to the welding gun. The consumable welding wire is continuously fed through the gun cable and the contact tube inside the gun, where an electrical connection is made to the power supply. In addition, the shielding gas and cooling water are also fed through the gun cable. The welding gun can be operated either man-

![Fig. 59.3 Composition of a typical GMAW machine and its components](http://www.robot-welding.com/welding_torch.htm, http://www.binzel-abicor.com)
or automatically, by a welding robot or some other automated setup. The gun shape is usually a swan-neck or straight. Guns with low current and light duty cycle are generally gas-cooled whereas those with higher current are water-cooled.

Formerly, welding machines were based on simple transformers with the operational frequency of the main energy source (i.e., 50 or 60 Hz). For DC welding, the transformer was equipped with a rectifier and an additional low-pass filter to suppress the ripples and produce a process-stabilizing effect. In modern inverter-type equipment (Fig. 59.4) the main conversion is performed at much higher frequency (approximately 20–50 kHz) allowing to decrease transformer weight, size, and magnetic losses (by about tenfold).

The output stage of the power supply may also include a controlled on/off switch circuit. By varying the on/off period (i.e., the pulse duty factor), the average voltage may be perfectly adjusted. For AC welding, the power source implements additional features such as pulsing the welding current, variable frequencies, variable ratio of positive/negative half-cycles, etc. This allows adjusting the square-wave shape to minimize the electrode thermal stress and the cleaning effect. In some cases, an AC sine wave is combined with high-frequency high voltage in the neighborhood of zero-crossing, to ensure noncontact arc reignition. Other variants use pulsed DC current of low-frequency (1–10 Hz) to reduce weld distortions and compensate cast-to-cast variations.

By relevant settings of welding parameters, it is possible to select three possible modes of operation (short arc mode, spray mode, and globular mode), which are distinguished by the way in which metal is transferred. The weld orientation relative to gravity, torch travel speed, and electrode orientation relative to the welding joint also have considerable influence on the weld formation. For most materials, electrode angles of 60–120° give welds with adequate penetration-depth-to-width ratio. In some cases, electrode cross-oscillation (weaving) is necessary. Other important control parameters are electrode feed speed, distance between the workpiece and contact nozzle, travel motion parameters (straight or weaving type), composition of shielding gas, and delivery of cooling gas/water.

### 59.3.2 Resistance Welding Equipment

The implementation of resistance spot welding involves coordinated application of force and current of the proper magnitude and time profile. Typically the current is in the range of 1–100 kA, and the electrode force is 1–20 kN. For the common combination “1.0 + 1.0 mm” sheet steel, the corresponding voltage between the electrodes is only 1.0–1.5 V, however the voltage from the power supply is much higher (5–10 V) because of the very large voltage drop in the electrodes [59.2–4].

The spot welding cycle is divided into four time segments: squeeze, heat (weld), cool (hold), and off, as shown in Fig. 59.5. The squeeze segment provides time to bring the electrodes into contact with the workpiece and develop full force. The heat segment is the interval during which the welding current flows through the circuit. The cool segment, during which the force is still held, allows the weld to be solidified, and the off segment is to retract the electrodes, and remove or reposition the workpiece. Typical values for the heat and hold times are 0.1–0.5 s and 0.02–0.10 s, respectively. In industry, the segment duration is often expressed in cycles of the main frequency (50 or 60 Hz).

Typical equipment for resistance welding includes the power supply with secondary lines, the electrode pressure system, and the control system. This structure applies to both spot and roller seam welding machines. Differences are in the type of electrode fittings and in the electrode shapes. For spot welding, the guns normally include a pneumatic or hydraulic cylinder and are designed to fit a particular assembly. The most common are C-type and X-type guns (Fig. 59.6), which differ in shape and force application mechanisms (in the first case, the cylinder is connected directly to the moving electrode; in the second case, it is connected via the lever arm). However, some new welding guns incorporate built-in electromechanical actuators for force generation.
Resistance welding may employ several power supply architectures that differ in the type of the current (AC/DC) and frequency of voltage conversion: AC power source based on a low-frequency (50 or 60 Hz) step-down transformer; DC power source with a low-frequency (50 or 60 Hz) transformer and rectifier; impulse capacitive-discharge source, where the rectified primary current is stored in capacitors and is transformed into high welding currents; inverter-based power source, where the primary supply voltage (50 or 60 Hz) is rectified and is converted to a mid-frequency (20–50 kHz) square wave. Similar to arc welding, the inverter-based method gives essential reduction of power supply size and weight. All methods may be used with single- or three-phase mains supply.

From a compositional point of view, there are two main types of resistance welding equipment. In the first type, an AC power unit with electric transformer is built directly into a welding gun. The second type uses a DC power unit with welding cables connected to the gun.

Modern computer-based control units allow programming of all essential process parameters, such as current magnitude, welding cycle times, and electrode force. Some sophisticated controllers also allow regulation of current during welding, control of pre/post-heat operations, or adjustment of the clamping force during the cycle. Particular values of the welding parameters depend on the physical properties and thickness of the joining materials, and also on the type of equipment used. Weld current shape is usually rectangular, but can also be trapezoid type with programmed rise/fall times. For some thick materials, several current pulses may be applied.

### 59.4 Welding Process Sensing, Monitoring, and Control

Automated welding requires accomplishing a number of tasks (such as weld placement, weld joint tracking, weld size control, control of the weld pool, etc.) that are based on real-time monitoring and control of relevant parameters. These actions must be performed in the presence of disturbances caused by inaccurate joint geometry, misalignment of workpiece and welding tool, variations in material properties, etc. The main challenge is that the observable data is indirectly related to final weld quality, so sensing and feedback control relies on a variety of techniques. Basically, they are divided into groups (technological and geometrical), which provide correspondingly control/monitoring of the welding process and positioning of the workpiece relative to the energy source [59.7, 8].

#### 59.4.1 Sensors for Welding Systems

For welding, technological parameters typically include voltage, current, and wire feed speed. The arc voltage is usually measured at the contact tube within the weld torch, but the voltage drop between the tube and the wire tip (where the arc starts) must be compensated. Another method is to measure the voltage on the wire inside the feeding system, which provides a more accurate result.

The welding current can be measured using two types of sensors, the Hall-effect sensor and current shunt. The former is a noncontact device that responds to the magnetic field induced by the current. The second sensor type employs a contact method where the current flows through a calibrated resistor (shunt) that converts the current into a measured voltage.
The \textit{wire feed speed} is usually estimated by measuring the speed of the drive wheel of the feeder unit. However, this must be complemented with special features of the feeder mechanics, which ensures robustness with respect to wire diameter variations and bending/twisting of the wire conduit.

Sensors for geometrical parameters provide the data for seam tracking during welding and/or seam searching before welding. These capabilities ensure adaptation to the actual (i.e., nonnominal) weld joint geometry and the workpiece position/orientation relative to the torch. The most common geometrical sensors are based on \textit{tactile}, \textit{optical} or \textit{through-arc} sensing principles.

\textit{Tactile sensors} implement purely mechanical principles, where a spring-loaded guide wheel maintains a fixed relationship between the weld torch and the weld joint. In more sophisticated sensors the signals from the mechanical probe are converted into electrical signals to acquire the geometrical data.

\textit{Optical sensors} usually use a laser beam, which scans the seam in linear or circular motions, and a charge-coupled device (CCD) array that captures features of the weld joint (Fig. 59.7a). By means of scanning, the sensor acquires a two-dimensional (2-D) image of the joint profile. When the welding torch and sensor are being moved, a full three-dimensional (3-D) description of the weld joint is created. By applying appropriate image processing techniques and the triangulation method, it is possible to compute the gap size and weld location with respect to the welding torch [59.9]. A laser-based optical sensor is typically mounted on the weld torch, ahead of the welding direction, and a one-degree-of-freedom mechanism is required to maintain this configuration during welding. A typical laser scanner provides a sweep frequency of 10–50 Hz and an accuracy of ±0.1 mm, which is sufficient for most of welding processes. However, high price often motivates the use of alternative sensing methods.

\textit{Through-arc sensing} is based on the measurement of the arc current corresponding to weaving (i.e., scanning) torch motions (Fig. 59.7b). This is a popular and cost-effective method for seam tracking in GMAW and related processes [59.10]. This method employs the relation between variations of the arc current and the electrode/workpiece distance, which is negative proportional for constant arc voltage. Typically, triangular-, sinus- or trapezoid-type motions are used, with a few millimeters of weaving amplitude, to achieve accuracy of about ±0.25 mm. For this method, geometrical information can be retrieved using continuous current measurement or its measurements at the turning and/or center points of the weaving motion. Correspondingly, different control principles are applied based on difference computing or template matching.

In practice, the tracking capability is usually combined with a search function (i.e., preweld sensing of the joint location), where the torch gradually moves in a predefined direction until detecting the weld joint. There are two basic methods for this function, which differ in terms of sensors and search patterns:

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig597.png}
\caption{Seam tracking using laser scanning (a) and through-arc sensing with weaving (b) (http://www.roboticsonline.com, http://www.thefabricator.com)}
\end{figure}
59.4.2 Monitoring and Control of Welding

Using data obtained from the sensors, it is possible to evaluate the weld quality and detect (or even classify) different weld defects, such as porosity, metal spatter, irregular bead shape, incomplete penetration, etc. These capabilities are implemented in monitoring systems, which usually use high-speed online analysis of welding voltage and/or current that are compared with preset nominal values or time patterns. Based on this analysis, an alarm is triggered if any difference from the preset values exceeds the given threshold. More sophisticated installations use computer-based image processing to evaluate the welding pool geometry and penetration depth [59.11].

To judge weld quality, the monitoring system relies on physical or statistical models, allowing the definition of alarm thresholds correlated with real weld defects or welding process specifications; for instance, for all GMAW processes, the voltage and current shape and mean values allows the detection of the metal transfer mode (short circuit, globular or spray transfer). In pulsed GMAW, the peak current is monitored and compared with preset values. For short-circuit GMAW, the monitoring features includes short-circuit time or frequency, as well as the average short-circuit current and the average arc current. In the general case, the features used for monitoring may be dependent on the specific algorithm and the welding condition.

For process feature analysis, various strategies are applied. The simplest ones employ deterministic decision making based on nominal values and tolerances, where any deviation from these is considered a potential cause of quality decrease. More sophisticated techniques employ template matching or treat the measured features as random variables and apply statistical methods such as control charts or spectrum analysis. However, the user must realize that increasing the detection probability often leads to false alarms that regularly interrupt the process. So, most current commercial monitoring systems utilize simple and robust algorithms, in which process features are averaged within user-defined time segments, filtered, and compared with a predefined threshold corresponding to normal welding conditions.

Welding process deviations detected via monitoring are to be compensated by control actions [59.12]. However, because of process complexity and indirect relevance of the observable data, simple feedback loops cannot be implemented. So, in addition to seam tracking, model-based strategies must be applied to enable adjustment of the welding equipment settings. However, in spite of its tremendous practical significance, this is still an active research area that employs various sophisticated decision-making techniques based on artificial intelligence and knowledge-based modeling.

59.5 Robotic Welding

Most industrial automated welding systems employ robotic manipulators, which are integrated with standard welding equipment that provides energy supply and basic control of welding parameters. The manipulators replace the human operator by handling the welding tool and positioning the workpiece. Usually this leads to an increase in quality and productivity, but poses a number of additional problems related to robot control, programming, calibration, and maintenance [59.13, 14].

59.5.1 Composition of Welding Robotic System

Currently, robots are mainly used for arc and spot welding processes. However, some recent applications deal with laser and plasma welding and also with friction stir welding. Typically, a robotic welding station includes a robot, a robot controller, welding equipment with relevant sensors, and clamping devices (fixture), allowing the workpiece to be held in the desired position in spite
of thermal deformations. In addition, there are a variety of auxiliary mechanisms that provide an increasing in the robot workspace, better weld positioning, safety protection, and workpiece transportation between workstations.

The most common design of an arc welding robotic station is shown in Fig. 59.8. Usually, the robot has six actuated axes, so it can access any point within the working range at any orientation of the welding torch. In most cases robots are implemented with a serial architecture with revolute joints, which ensures larger workspaces (Fig. 59.9). Typical arc welding robots have a working envelope of 2000 mm and payload capacity of about 5 kg, which is sufficient for handling welding tools. To extend the working range, robots may be installed in an overhead position. A further extension of the working range can be achieved by installing the robot onto a linear carriage with auxiliary actuated axes (track, gantry or column). The wire feed unit and the spool carriers for the wire electrodes are often fixed to the robot, but can also be placed separately. In many cases the torch is equipped with shock absorption devices (such as springs) to protect it against collisions.

The workpiece positioners allow the location of seams in the best position relative to gravity (i.e., *downhand*) and to provide better weld accessibility. They usually have one or two actuated axes and may handle payload from a few kilograms to several hundred tons. The most common positioners are *turnover*, *turn-tilt*, and *orbital tables*, but *turning rolls* are also used to rotate the workpiece while making circular seams (in tank manufacturing, for instance). Positioners with orbital design have an advantage for heavy parts, allowing rotation of the workpiece around its center of gravity. In some cases, positioners are implemented with a multitable architecture, in which the operator feeds and removes the welded workpiece on one side, while the robot is welding on the other side. The positioner axes may either turn to certain defined positions (*index-based control*) or be guided by the robot controller and moved synchronically with the internal axes.

For spot welding, the robot payload capacity is essentially higher (about 150 kg), being defined by rather...
heavy equipment mounted on the robotic manipulator arm. Usually, each spot welding station includes several robots working simultaneously to provide the same cycle time along the manufacturing line. An example of a spot welding line for car manufacturing is presented in Fig. 59.10. For such applications, robots usually perform several thousands welds on over a hundred parts with a cycle time of about 1 min. Besides the joining and handling operations, the robots also ensure online measurement and inspection by means of dedicated laser sensors.

To ensure coordination of all components of the automated welding system, a relevant multimicroprocessor control architecture usually comprises two hierarchical levels. At the lower level, the local controllers implement mainly position-based algorithms that can receive a desired trajectory and run it continuously (for each actuated axis separately, but simultaneously and coordinated). High-level controllers ensure trajectory correction in real time, as a function of the observed results of the welding process. Some robot controllers can be connected via the Internet with telediagnostic systems to support service personnel during troubleshooting.

59.5.2 Programming of Welding Robots

To take advantage of robotic welding, especially in small-batch manufacturing, it is necessary to reduce the prewelding phase (or setup time), which includes selection of welding parameters and generation of control program defining motions of the robot, positioner, and other related mechanisms. This process is time consuming and may be longer than the actual welding phase [59.16].

For selection of welding parameters, there are at present a number of generally accepted databases. They allow the definition of optimal values of the welding current, voltage, welding speed, wire diameter, and number of weld beads/layers depending on type of weld, welding position, properties of materials, plate thickness, etc. Also, these databases usually provide interface to computer-aided design (CAD) models of the joining components to simplify extraction of geometrical information.

For robot programming, two basic methods exist: online (programming at the robot) and offline (programming out of the robot cell). The former method, which is also referred to as manual teaching, requires extraction of the robot from the manufacturing process and involves operator-guided implementation of all required motions. The operator uses a dedicated teach-pendant to move the welding torch to notable points of the weld, to store the torch position and orientation, and to create corresponding motion commands with necessary attributes (defining velocity, type of interpolation along the path, weave pattern, welding parameters, etc.).

The simplest implementation of the offline programming uses an external computer to create a text file describing the sequence of motions, but the command arguments (i.e., torch position and orientation) are obtained via manual teaching. Nevertheless, this offers essential shortening of programming time because of extensive use of standard macros.

Advanced offline programming systems provide fully autonomous program generation, completely outside of the manufacturing cell. They rely on so-
phisticated photorealistic 3-D graphical simulation of the robotic system and parts to be welded, allowing the required torch coordinates/orientations to be obtained directly from the models. Moreover, modern CAD-based robotic programming systems [such as emWorkplace (Robcad), IGRIP, CimStation, etc.] provide an interface to all standard 3-D modeling systems and incorporate a number of additional tools for robotic cell design, layout optimization, graphical simulation of the movements, program debugging and verification with respect to collisions and cycle time, program downloading to the robot controller, unloading of existing programs for optimization, etc. An example view of a CAD-based simulation and programming environment is presented in Fig. 59.11. However, while using the offline programming, it is necessary to ensure good correspondence between the nominal CAD model of the robot and its actual geometrical parameters. In practice, this is not a trivial problem, which is solved via calibration of all geometrical parameters describing the workcell components and their spatial location.

Automation of robot programming is still an active research area, which is targeted to replace movement-oriented program development to task-oriented programming. The final goal is automatic generation of robot programs from CAD drawings and welding databases, similar to programming methods for computer numerical control (CNC) machines.

59.6 Future Trends in Automated Welding

At present, welding automation is on the rise because of stricter customer demands and a shortage of skilled welders. So, equipment manufacturers and system integrators are enhancing their production and implementing more advanced technologies. The most important technology-oriented directions defining future trends in welding automation are the following [59.17–20]:

- **Improvement of traditional welding processes** with respect to productivity and environmental issues (including development of better controllable power sources, new electrodes, shielding gases and fluxes; using twin-arc and tandem-arc torches)
- **Industrial implementation of new efficient and environment-friendly processes**, such as laser beam and electron beam welding, friction stir welding, and magnetic pulse welding (including development of new energy sources, relevant control algorithms, manipulating equipment)
- **Creating new knowledge-based welding process models** with ability for online learning and capability for online feedback control of essential process features (such as molten pool geometry, heat distribution, surface temperature profile, thermal deformations)
- **Development of advanced sensors and intelligent seam-tracking control algorithms** (to compensate for parts’ mechanical tolerances in 3-D or 6-D space, and making welds in nonflat positions)
- **Development of new process monitoring and non-destructive evaluation methods** (using model-based condition monitoring and failure analysis techniques, and online ultrasonic and laser-based testing)

Concerning mechanical components (robotic manipulators, positioners, etc.), it is recognized that their current performance satisfies the requirements of most welding processes with respect to ability to reproduce the desired trajectory with given speed and accuracy. Future developments will focus on automation of robot programming and integration with other equipment:

- **Task-oriented offline programming and integration with product design** (using simulation-based methods; simultaneous product and fixture design; implementing 3-D virtual-reality tools and concurrent engineering concepts; developments of human–machine interfaces)
- **Standardization** of mechanical components, control platforms, sensing devices and control architectures (to reduce the system development time/cost and simplify its modification)
- **Monitoring of the welding equipment and robotic manipulators** (to predict or detect machine failures and reduce downtime using predefined exception-handling strategies)

In addition, there are a number of essential issues that are not directly linked with welding technology and equipment. These include marketing aspects, and also networking and collaboration using modern e-Manufacturing concepts.
59.7 Further Reading


References

59.3 W.A. Bowditch, K.E. Bowditch, M.A. Bowditch: Welding Technology Fundamentals (Goodheart-Willcox, South Holland 2005)
59.5 H.B. Cary: Arc Welding Automation (Marcel Dekker, New York 1995)


