Robotic Welding

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Abstract

Robotic welding is continued to be one of the most popular applications of robots. Traditionally, spot welding process has been the biggest use of robots especially in the automotive industry. As the robot becomes cheaper and easier to program, there are increasing implementations of robotic welding systems in many other industries such as shipbuilding, offshore, construction, and job shops. This chapter gives an overview of the types of robotic welding systems and their key components. It focuses on the arc welding processes which have been dominantly used in the various industries. The critical features of the robotic welding system for maximizing the welding quality, operational flexibility and productivity are discussed. These features are in the robot configurations, sensing, programming, workpiece handling, as well as welding process control.

Introduction

Robotic welding has been one of the most common and successful applications of robots in several industries. The earliest extensive application of welding robots started in the automotive industry in 1980s mainly for the resistance spot welding process. With the advent of the sensors and process control capabilities as well as advanced robot programming technology, welding robots are not just implemented for the high-volume production but have also been introduced for low-volume tasks. Such tasks are common in the industries of shipbuilding, offshore, and structural assemblies. Figure 1 shows several examples of robotic welding.

Many industrial welding applications benefit from the introduction of the welding robots since most of the drawbacks attributed to the human factors are eliminated as a result. The key benefits of robotic welding include increased welding quality and productivity and lower production cost, which lead to cheaper and better-quality products.

A typical robotic arc welding system includes an articulated six-degree-of-freedom (DoF) robot manipulator, welding power source, welding torch, wire feeder, positioner, welding torch cleaning and calibration station, fume extraction, and safety fence. More advanced robotic system equips with optical seam tracking system for complex welding processes which involve large number of passes. The basic functionalities of a robot welding system include welding, welding path programming, through-the-arc or optical seam tracking, as well as welding process monitoring and control.

Operation of the welding robot in general involves two stages. In the setup stage the operator inputs the welding parameters and programs robot path. It is followed by the welding stage where the robot performs the welding process. In the setup stage, the user determines the welding process and procedure. This could be the selection of the preprogrammed job orders where the welding parameters and the robot paths are defined. The setup stage can also be one for programming the robot to weld a new workpiece. In such a setup stage, in addition to the welding process setting, the operator will also input the operational parameters such as number of

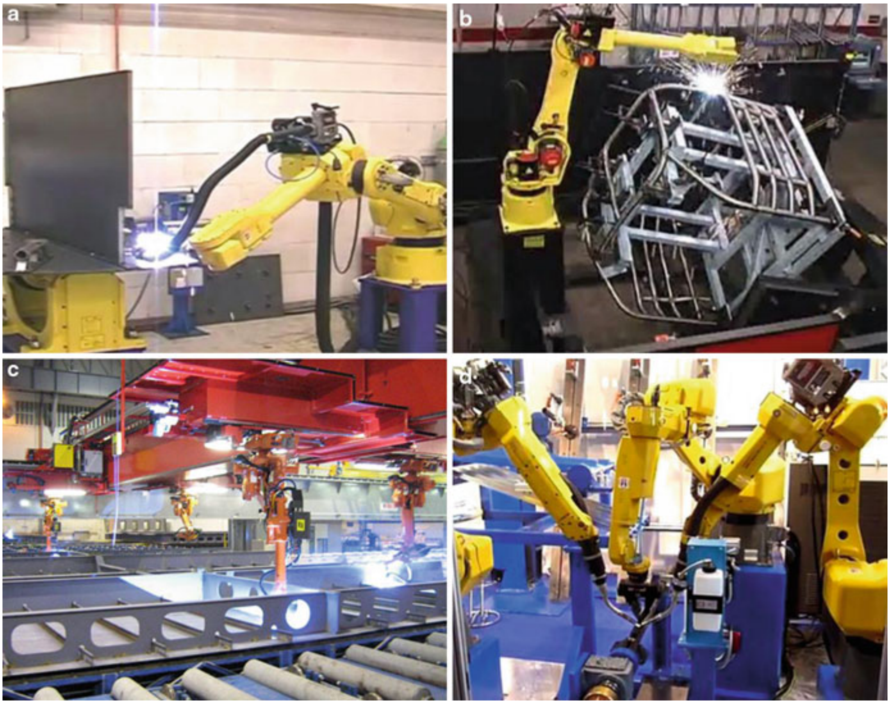

Fig. 1 Examples of robotic welding: (**a**) welding a workpiece on a turntable (www.forster-welding-systems.com), (**b**) welding a car frame (www.lincolnelectric.com), (**c**) robot panel welding for shipyard automation (www.kranendonk.com), (**d**) arc welding station with two welding robots and one workpiece handling robot (www.forster-welding-systems.com)

parts, motion of the workpiece positioner, teaching the robot welding path, and selection of the welding parameters.

In the welding stage, seam tracking may be used to guide the robot along the seam. In general, through-the-arc sensing is a common method for seam tracking. During the welding stage, the workpiece may be moved by the positioner to allow full accessibility for the welding torch held by the robot as well as for maximizing productivity.

Welding Processes

Welding is a process of permanent joining two materials (usually metals) through localized coalescence resulting from a suitable combination of heat, pressure, and metallurgical conditions. In order to obtain satisfactory welds, it is desirable to have:

- A source of energy to create union by fusion or pressure
- A method for removing surface contaminants

- A method for protecting metal from atmospheric contaminants
- Control of weld metallurgy

The solid and unified connection produced is called a weld joint. There are five basic types of weld joints, i.e., the butt, corner, tee, lap, and edge joints. The joints are made with many different types of welds. The most common types of welds are the bead, surfacing, plug, slot, fillet, and groove. Welding can be performed at flat, horizontal, vertical, and overhead positions (Jenney and O'Brien 2001).

Welding is the most economical and efficient way to join metals permanently in terms of material usage and fabrication costs. It is a common method to join all of the commercial ferrous and nonferrous metals of different types and strengths. It is indispensable for fabricating and repairing metal products with wide applications in automotive, construction, marine and offshore, and aerospace industries.

There are many different types of welding processes (Jenney and O'Brien 2001) which in general can be categorized as fusion and solid-state welding. For fusion welding the base and/or filler materials are melted, while solid-state welding processes do not involve the melting of the materials being joined. Fusion and solid-state welding processes can be classified as follows based on the source of energy:

- Fusion welding
  - Gas welding
  - Arc welding
  - Resistance welding
  - Energy beam welding
- Solid-state welding
  - Friction welding
  - Ultrasonic welding
  - Explosive welding
  - Forge and diffusion welding

The most suitable welding processes for robotic applications include resistance spot welding (RSW); gas metal arc welding (GMAW); gas tungsten arc welding (GTAW); laser beam welding (LBW); hybrid laser arc welding (HLAW); and friction stir welding (FSW) (Pires et al. 2005).

Resistance Spot Welding (RSW)

Resistance spot welding (RSW) is one form of resistance welding processes in which heat is generated from the workpiece's resistance to the flow of welding current and with the application of pressure. In resistance spot welding, the welding current and pressure is applied through copper alloy electrodes that concentrate the high electricity current and high contact pressure in the area of the weld to establish a permanent joint. The most critical parameters for resistance spot welding are time, current, and force. Figure 2 illustrates the resistance spot welding process.

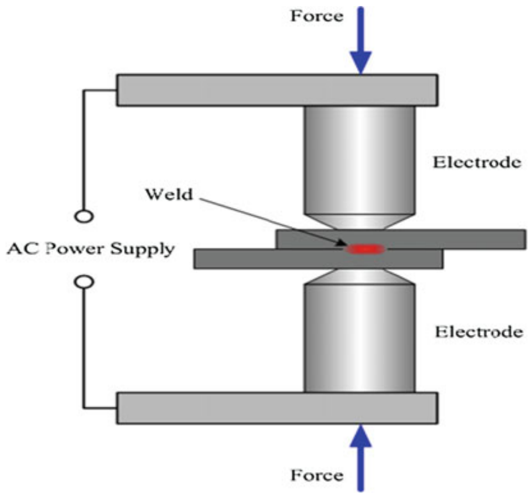

Fig. 2 Schematic illustration of resistance spot welding

Resistance spot welding is well established for sheet metal joining where a continuous seam is not required. Materials suitable for resistance spot welding include steel, aluminum, and galvanized steel. The entire process only takes a fraction of a second, is easy to handle, requires no additional materials, such as gas or wire, and is easy to automate. This makes it the ideal application for mass production of vehicle bodies or the processing of large format panels outside the automotive industry in the fields of apparatus engineering, electronic systems, and the manufacture of domestic appliances. Mainstream robot manufacturers supply six-DoF resistance spot welding robots integrated with a welding gun and welding system which generates the current and pressure needed.

Conventionally, a resistance spot welding gun is driven pneumatically to generate the pressure. In recent years, it has become increasingly popular to use a spot welding gun driven by an electric servomotor (Niu et al. 2008). The welding gun becomes the seventh robot axis and synchronized gun and robot motions can be programmed and executed. Moreover, the servomotor's torque can be more precisely controlled. These make resistance spot welding faster, more precise, reliable, and efficient. Major automotive manufacturers such as Renault, Mazda, Toyota, and Ford choose servo welding equipment for their car body assembly lines instead of conventional pneumatic equipment.

An innovative resistance spot welding process, DeltaSpot, was introduced by welding power source manufacturer Fronius in 2006 to join difficult materials such as high-strength steel and aluminum sheets. The defining feature of DeltaSpot is the robot welding gun with running process tape that runs between the electrodes and the sheets being joined as shown in Fig. 3 (Robotics On-line, Fronius 2012).

The process tape performs several very different functions (Robotics On-line, Fronius 2012) as follows:

Fig. 3 Resistance spot welding gun with a running process tape

Fig. 4 DeltaSpot for joining a 1.5 mm thick stiffening plate onto a 2 mm thick die-cast aluminum door frame

- Prevent direct contact between the electrode and the workpiece to protect the electrodes from soiling or other influences emanating from the surface of the workpiece.
- Improve the contact situation: for every single spot, the process tape creates a new electrode contact surface to the workpiece.
- Influence the heat balance in the workpiece directly and selectively.

The benefits of using running process tape include completely reproducible spot welds, excellent process reliability, less surface spatter, increased service life for electrodes, and the capability to produce top-quality joints between sheets made of different materials, even when they are of different thicknesses. One example shown in Fig. 4 is a 1.5 mm thick stiffening plate being spot welded onto a 2 mm thick aluminum die-cast door frame (Fabricating 2012).

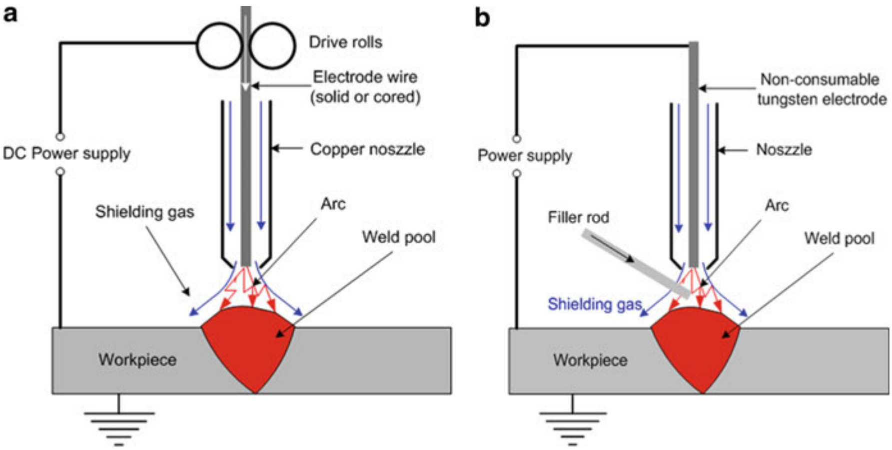

Fig. 5 Schematic illustration of (**a**) GMAW and (**b**) GTAW

Gas Metal and Gas Tungsten Arc Welding (GMAW and GTAW)

Gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW) are both arc welding processes. In arc welding processes, an AC or DC welding power source is used to ignite and maintain an electric arc between an electrode and the base material to melt the metals. Figure 5 illustrates the GMAW and GTAW arc welding processes.

Gas metal arc welding (GMAW) is also referred as metal inert gas (MIG) or metal active gas (MAG) welding. Consumable electrode wire, having chemical composition similar to that of the base material, is continuously fed from a spool to the arc zone. An electric arc is created between the tip of the wire and the weld pool. The wire, which is usually solid wires, is progressively melted and added into the weld pool through various metal transfer modes and forms part of the weld pool. In general, there are four modes of metal transfer, e.g., short-circuit, globular, axial and pulsed spray transfer. Metal transfer mode depends upon the arc current, voltage, base and filler materials, electrode diameter, polarity and type of shielding gas.

Both the arc and the weld pool are protected from atmospheric contamination by a shielding gas, which is delivered through a nozzle that is concentric with the welding wire guide tube inside the welding torch. The shielding gas or gas mixture may consist of inert gas, such as argon, or active gas like CO_2, or a mixture of inert and active gases. The most critical parameters for GMAW include the following: voltage, wire feed rate (current), travel speed, arc (stick-out) length, shielding gas, wire diameter, and polarity (DC+ electrode positive (DCEP) or DC- electrode negative (DCEN)) as DC power source is usually used for GMAW).

There are two variants of the GMAW process, which are flux-cored arc welding (FCAW) and metal-cored arc welding (MCAW). There are many common features between the three processes that they are all arc welding with consumable wire

Table 1 Differences among GMAW, FCAW, and MCAW

	GMAW	FCAW	MCAW
Wire type	Solid wire	Tubular construction flux-cored wire with an outer metal sheath being filled with fluxing agents plus metal powder. The flux fill is used to provide alloying, arc stability, slag forming, deoxidation, and gas shielding with some wires	Tubular construction metal-cored wire with an outer metal sheath being filled entirely with metal powder, except for a small amount of nonmetallic compounds. They are added to provide some arc stability and deoxidation
Wire feeder	Normal feed rolls	Knurled feed rolls	Knurled feed rolls
Shielding gas	Shielding gas	Shielding gas and self-shielding (production of shielding gas by decomposition of fluxing agents within the wire)	Shielding gas
Slag cover	No slag	Slag cover	No slag
Transfer mode	Short-circuit, globular, axial or pulsed spray	Short-circuit or globular	Short-circuit, axial or pulsed spray

electrodes. However, there are also several fundamental differences, which are summarized in Table 1.

GMAW process can be used to weld almost all metallic materials, in a wide range of thickness from 0.5 mm up to 30 mm or more, and is effective in all positions. GMAW is a very economical process because it has higher travel speed and deposition rate and does not require frequent stops to change electrodes. In addition, minimal post weld cleaning is needed because slag is almost absent, especially in solid-wire GMAW. These advantages make the process very well adapted to be automated and particularly to robotic welding applications. About 80 % of robotic arc welding is GMAW welding.

To further increase the travel speed and deposition rate, dual-wire or twin-wire GMAW process was developed (The Lincoln Electric Company 2003). In dual-wire GMAW process, two wires are continuously fed through a special welding torch and are consumed to form a single molten pool. Both wire electrodes' arcs contribute to a common weld pool, but each is independently controlled by its own power source. The first electrode, the "lead," controls deposition rate and penetration. The second electrode, the "trail," controls weld bead appearance. Systems normally comprise two separate wire feed units and two power sources, so the wires can be operated independently, i.e., with different wire diameters, current levels, or operating modes (continuous or pulsed). In pulsed mode, the current in each wire is pulsed alternately to avoid magnetic interactions between the two arcs. Welding commonly takes place with the two wires in line along the joint line, although the torch can be rotated across the joint to give a wider weld bead. Figure 6 illustrates

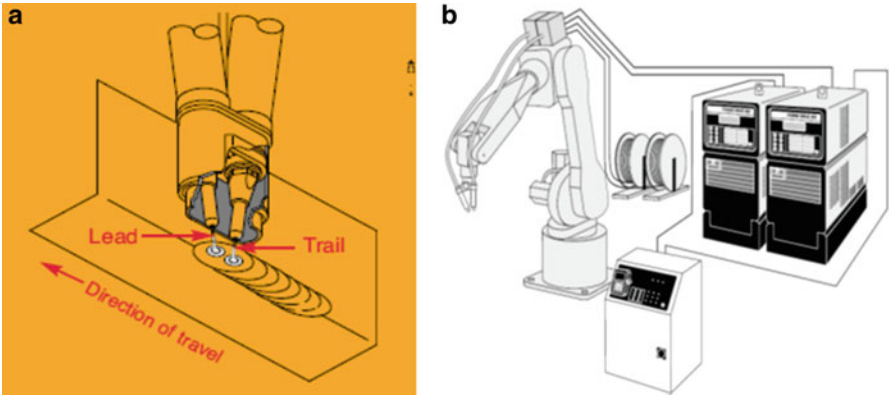

Fig. 6 Schematic illustrations of (**a**) dual-wire GMAW process and (**b**) its robotic system configuration

dual-wire GMAW process and its robotic system configuration. This technology can only be used for mechanized or robotic welding because of the precision required in positioning the bulky torch. Joint accessibility is also restricted because of the torch size.

Another development of GMAW is to reduce the heat input. The technology is called cold metal transfer (CMT) by incorporating the wire motions directly into the process control (Fronius 2014). During the arc period, the filler metal is moved towards the weld pool. When the filler metal dips into the weld pool, the arc is extinguished and the welding current is lowered. The rearward movement of the wire assists droplet detachment during the short circuit. The wire motion is then reversed and the process begins all over again. This makes the process alternating between hot and cold periods. Still maintaining the high speed and high deposition rate of a GMAW process, CMT technology makes the arc more stable and the welding process spatter free. It also enables GMAW process applicable for very thin sheet welding. Figure 7 illustrates the alternating hot and cold periods in CMT welding.

Gas tungsten arc welding (GTAW) is also commonly referred to as tungsten inert gas (TIG) welding. GTAW uses the heat generated by an electric arc struck between a nonconsumable tungsten electrode and the workpiece to fuse metal in the joint area and produce a molten weld pool. The arc is shrouded in an inert gas shield to protect the weld pool and the nonconsumable electrode. The process may be operated autogenously without filler or filler may be added by feeding a consumable wire or rod into the established weld pool. GTWA can be run on either DC or AC current. The most critical parameters for GTAW include welding current, arc length (voltage), travel speed, shielding gas, and polarity if DC power source is used.

DCEN is the most common mode of operation and is widely used for welding carbon, alloy, and stainless steels, as well as nickel and titanium alloys.

Fig. 7 Illustration of the hot and cold periods during CMT

Copper alloys, with the exception of those containing aluminum in significant amounts, can also be welded with this polarity. DCEP is used for aluminum alloys when welding with pure helium as the shielding gas, while AC is used most commonly when welding aluminum and its alloys with pure argon or argon-helium mixtures. There are several variations of the GTWA process designed to improve productivity and they are orbital, hot wire, and narrow-gap GTAW.

Different from GMAW, heat input in GTAW does not depend on the filler material feed rate. Consequently, the process allows a precise control of heat generation and the production of superior quality welds, with low distortion and free of spatter and little particulate fume. The process is very versatile and may be used to weld any metal or alloy system and over a wide range of thickness but is usually restricted to 10 mm and under for economic reasons. It is particularly suited to welding of sheet materials and for putting in the root pass of pipe welds. However, due to its relatively slow deposition rate, it is not regarded as a high-productivity process.

Mainstream robot manufacturers usually work together with welding power source suppliers to provide total solutions for various GMAW and GTAW welding applications. The system is comprised of robots, fixtures and positioners, welding power sources and torches, wire feeders (for GMAW process), controllers, and weld sensing and monitoring module.

Laser Beam and Hybrid Laser Arc Welding (LBW and HLAW)

Laser Beam Welding (LBW)

The term laser is the abbreviation for “light amplification by stimulated emission of radiation.” As a stimulated emission, laser beam is monochromatic and coherent in phase and has very small divergence. With the advancement of laser technology, lasers have been introduced into metal welding as heat source since the 1970s. Gas (CO_2) laser at 10.6 μm wavelength and solid-state (Nd:YAG) laser at 1.06 μm wavelength are the two main types of laser for welding applications. The powers for CO_2 lasers are approximately from 5 to 20 kW and can reach up to 60 kW. For Nd:YAG lasers, average output powers of up to several kW are obtainable (ISF Aachen 2013a).

In recent years, several other types of solid-state lasers such as Nd:YAG disk laser (1,030 nm wavelength), diode/semiconductor laser (920–1,050 nm wavelength), and Ytterbium fiber (1,070 nm wavelength) laser have been developed to the stage where power levels suitable for metal welding are available. With advantages of compact and modular design, high energy efficiency, good beam quality, high metal absorption, low maintenance, and operating cost, these solid-state lasers are also finding applications in metal welding.

Laser beams need to be focused to a small spot to generate high power density for welding. For CO_2 laser, beam focusing is normally carried out with mirror optics such as transmissive lens or reflective mirrors. Nd:YAG and the other solid-state lasers can be transmitted through fibers and then focused by focusing optics. Fiber-coupled solid-state and fiber lasers are more flexible for robotic applications. Laser beam can even be distributed into several welding stations through beam deflecting or splitting.

Conventionally, after focusing, laser beam positioning is through moving either the laser head or the workpiece. An alternative beam positioning method is the 3D scanner technology for solid-state and fiber lasers whose excellent beam quality enables long focal lengths. For example, moveable mirrors and optical elements, such as Z-adjustable collimator unit, galvanometric scanner, and focusing device, are integrated in the 3D scanner. Figure 8 gives two examples of the design of the scanners from ScanLab (ScanLab 2013; Schulze and Lingner 2013).

The scanner allows the use of laser as a highly dynamic and flexible tool and enables fast, precise, and fine positioning of the laser spot in three dimensions. The scanner can also be guided over a workpiece in conjunction with a robot. The robot and the scanner synchronize their movements in real time to realize remote 3D welding and "welding on the fly."

Having high power and small laser spot, laser power intensity can reach as high as 10^{12} W/cm^2. Thus, laser beam welding is one form of high power density welding processes. There are two basic modes by which laser welding can occur in metals: heat conduction welding and keyhole (deep penetration) welding, which are illustrated in Fig. 9.

Heat conduction welding usually occurs when laser power intensity is less than 10^5 W/cm^2. In heat conduction welding, the materials to be joined are melted by absorption of the laser beam at material surface. Welding penetration depths in this mode are typically below 2 mm.

Above the threshold intensity of 10^6 W/cm^2, local heating reaches evaporation temperature and laser-induced plasma develops. The plasma absorbs an increased quantity of laser radiation. A vapor cavity (keyhole) forms and allows the laser beam to penetrate deep into the material through multiple reflections inside the keyhole. The keyhole, which is moved through the joining zone and is prevented from closure due to the vapor pressure, is surrounded by the largest part of the molten metal. The residual material vaporizes and condenses either on the keyhole side walls or floes off in an ionized form. Given sufficient laser power, weld depth of up to 25 mm in steel can be achieved.

For laser beam welding, the most critical parameters include laser type and mode, laser power and/or pulse width and frequency for pulse laser, laser beam

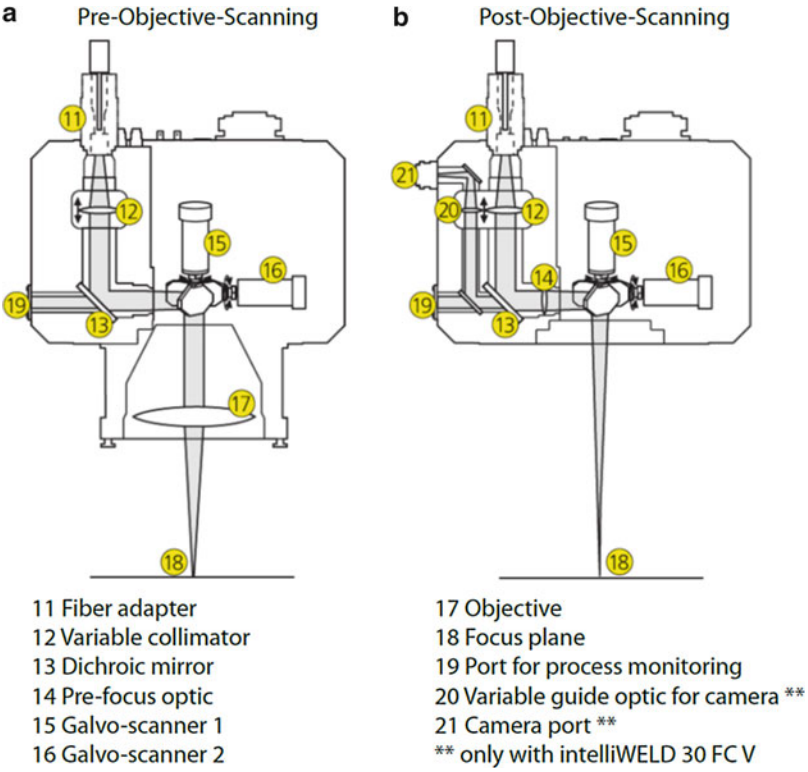

Fig. 8 Schematic illustrations of 3D laser scanners

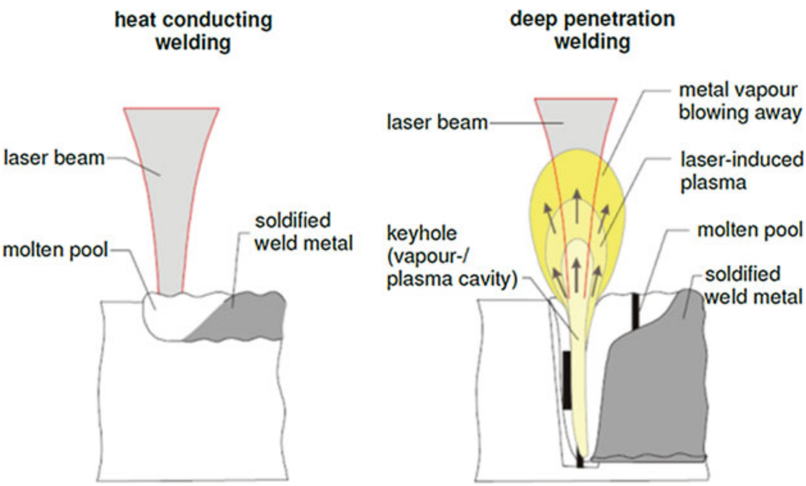

Fig. 9 Schematic illustrations of heat conduction and deep penetration modes in laser welding (ISF Aachen 2013a)

Table 2 Advantages and disadvantages of laser beam welding

	Advantages	Disadvantages
Process	High power density	High reflection at metallic surfaces
	Small beam diameter	Restricted penetration depth (≤25 mm)
	High welding speed	
	Noncontact process	
Workpiece	Minimum thermal stress	Expensive edge preparation
	Little distortion	Exact positioning required
	Welding at positions difficult to access	Danger of increased hardness and cracks due to high cooling rate
	Different materials weldable	Aluminum and copper difficult to weld due to high surface reflectivity
Installation	Short cycle time	Expensive beam transmission and forming
	Operation at several stations possible	Power losses at optical devices
	Well suitable to automation	Laser radiation protection required
		High investment cost
		Low energy efficiency especially for CO_2 and Nd: YAG laser

quality, focusing condition, welding speed, shielding gas, and joint type. Compared to conventional welding methods, the most important advantages and disadvantages of laser beam welding are summarized in Table 2 (ISF Aachen 2013a).

Hybrid Laser Arc Welding (HLAW)

One challenge of laser beam welding is that it requires precise workpiece fit-up and accurate alignment of the beam with the joint edge. To address this challenge, hybrid laser arc welding (HLAW) is developed coupling the gap bridging capability of the traditional arc welding process. In hybrid laser arc welding process, the laser beam as a high power density heat source commonly serves as the primary heat source enabling deep penetration mode welding while the arc as the secondary heat source controls the weld bead formation. As a secondary heat source, either GMAW or GTAW can be chosen depending on if any addition of filler material is required. The weld penetration increases with an increase in laser energy, whereas the weld width increases with the arc energy. For different applications, there exists an optimum energy ratio between the two heat sources. Figure 10 illustrates hybrid laser arc welding process with the laser leading the GMAW arc (The Lincoln Electric Company 2011).

Hybrid laser arc welding process combines the advantages of both laser beam and arc welding. They are as follows:

- High speed and deep penetration of laser beam welding
- Wide molten pool of arc welding reducing the demands on edge preparation and beam-edge alignment
- Improved weld metallurgy due to slower cooling rate lowering the occurrence of cracks and too high hardness welds

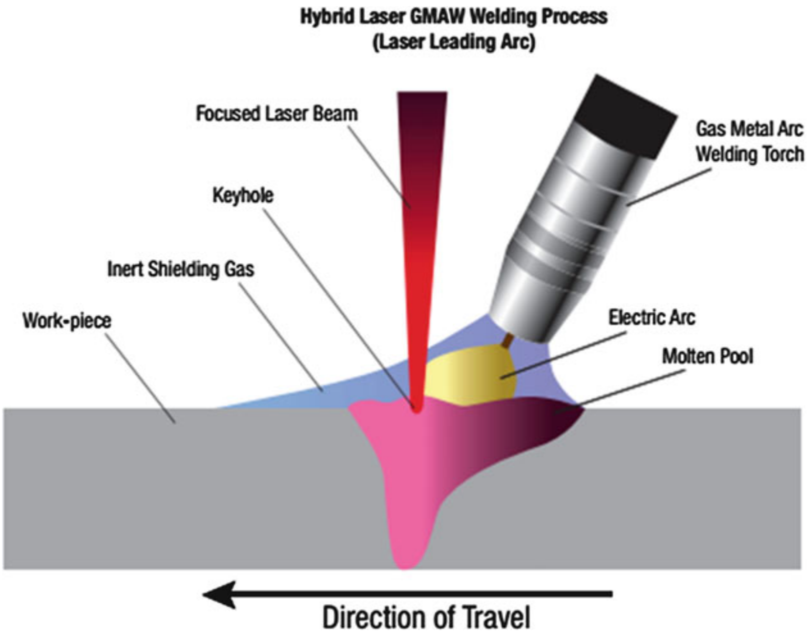

Fig. 10 Schematic illustration of hybrid laser arc welding process (The Lincoln Electric Company 2011)

The materials that may be welded with laser or hybrid laser and arc range from unalloyed and low-alloy steels up to high-quality titanium and nickel-based alloys. High carbon content steels may have a problem of too high hardness weld due to the high cooling rate of laser beam welding. Aluminum and copper alloys are relatively difficult to be welded by lasers due to its high reflectivity to laser and the loss of low-evaporation temperature alloy elements such as zinc and magnesium. Both laser beam and laser arc hybrid welding find applications in automotive, aerospace, electronic, steel, and medical industries.

Mainstream robot suppliers such as ABB, KUKA, Kawasaki, Yaskawa, and Fanuc and some welding power source suppliers, such as Fronius and Lincoln, work together with laser system manufacturers including Rofin-Sinar, Trumpf, and IPG to provide robotic laser and hybrid laser arc welding systems. The system is comprised of robots, fixtures and positioners, laser beam sources, controllers, laser transmission, focusing, and positioning devices, and sensing and monitoring systems.

Friction Stir Welding (FSW)

Friction stir welding (FSW) is a solid-state welding process. Friction stir welding is performed by rotating a nonconsumable tool which is plunged into the material to be welded until the shoulder of the tool contacts the top surface of the plate. The tool is then traversed along the joint line to create a solid weld. The material around

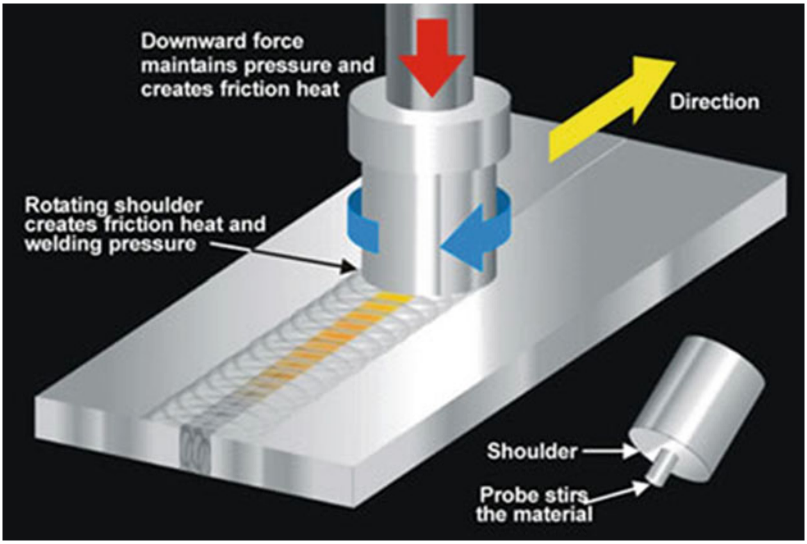

Fig. 11 Schematic illustration of friction stir welding process and tool (ESAB 2013)

the tool becomes softened and highly plasticized from the frictional heat generated during the process and is carried around the tool so that there is a complete mixing of materials from the two plates. In full penetration welding the tool probe extends almost through the thickness of the plates to be welded, but in partial penetration the probe can be much shorter. Because there is no melting or resolidification of material, there is usually lower distortion introduced by this welding process compared with other welding processes. The process can be used to make butt and lap joints in any orientation. Due to the high forces developed during the process, the plates must be rigidly clamped during welding. A tool tilt angle is usually used to aid material compaction behind the FSW tool. Figure 11 illustrates the friction stir welding process and tool (ESAB 2013).

Initially, friction stir welding is mainly used for joining low melting point metals and alloys, such as aluminum, magnesium, and copper alloys. And the tool material normally used is high carbon steel. With the development of tools which can withstand high temperature and stress, such as tools made of W-Rhenium, polycrystalline cubic boron nitride (PCBN), and ceramic, friction stir welding can now be used for joining of higher melting temperature materials including steels, titanium, and nickel-based alloys.

Friction stir welding process parameters include tool geometry, tool rotational and traverse speed, tool tilt angle and pin plunge depth. Compared to conventional arc welding processes, friction stir welding has the following advantages:

- Low thermal distortion
- Good dimensional stability

- No loss in alloying elements
- Excellent metallurgical properties
- Fine microstructure
- No cracking, porosity, and other welding defects
- Environmental friendly/green welding technology
  - No shielding gas
  - No use of chemical for cleaning
  - No slag and fumes
  - Highly energy efficient

Friction stir welding is easy to automate to weld in any position and follow complex 3D weld paths. Robotic friction stir welding is being developed by robot companies like Kawasaki, Fanuc, and ABB; welding companies and research institutes such as ESAB, TWI, GKSS, and CRIQ; and system integrators like Friction Stir Link, Inc.

Robotic Welding Systems

Depending on the welding processes, robotic welding system can be mainly classified in arc welding robots, spot welding robots, and laser processing robots. Each of them comprises the typical components such as robot manipulator, welding equipment, and positioner. In terms of the configuration, the robot welding system can be in the form of cell, where typically the welding robot is stationary, and the gantry robotic system where the robot arm is transferred to cover the large and usually stationary workpiece.

Types of Robotic Welding System Configurations

Key feature of welding robot is a robot manipulator with its end effector as a welding torch. The robot manipulator typically is mounted at a fix location surrounded by the auxiliary equipment and the workpiece holders. Such robotic configuration is called a robotic cell. There are other types of configurations for welding operation depending on the workpiece size and welding environments.

Stationary Robot and Workpiece

The most common configuration of a robotic welding system is one that all the components occupy within a confined area. Both the robot and the workpiece supported, respectively, by the base and positioner do not move relative to each other.

Often it is a standard product supplied by the robot manufacturers for job shops of metal parts and assemblies fabrications. There are portable welding cells where all the components are mounted on a platform and enclosed within a cabinet, as shown in Fig. 12. A robot cell comprises of a robot arm, a workpiece positioner, the

Fig. 12 Robotic welding cell (Kawasaki Robotics)

welding equipment, and welding safety curtains. Depending on the productivity requirements and the size of the workpiece, more than one robot can be integrated in the cell. Coordinated motions are preprogrammed for robot(s) and the workpiece positioners to reduce the cycle time and to facilitate the weld seam access as well as allowing better weld quality.

Moving Robot and/or Workpiece

When the welding points or seams are beyond the reach of the robot, the robot or the workpiece can be mounted on a gantry, a track, or a column. Such a configuration has the advantages of enlarged work space and increased flexibility and productivity. For example, it is possible that multiple workpieces can be welded by a single robot or multiple robots, thereby idle time in workpiece transferring can be minimized. An advanced feature of such configurations is that all the motions, including the robot, the positioner, and the transfer units, are coordinated or synchronized to maximize the arc/welding time.

The decision if the robot which carries the welding equipment or the workpiece should be made stationary depends on the weight and size of the workpiece. Generally the lighter of the two will be made moving. Example of such arrangement is the automotive assembly line where the robots are stationary and the car assemblies moved by the conveyor. Such a configuration is often found in high-volume production of large workpieces.

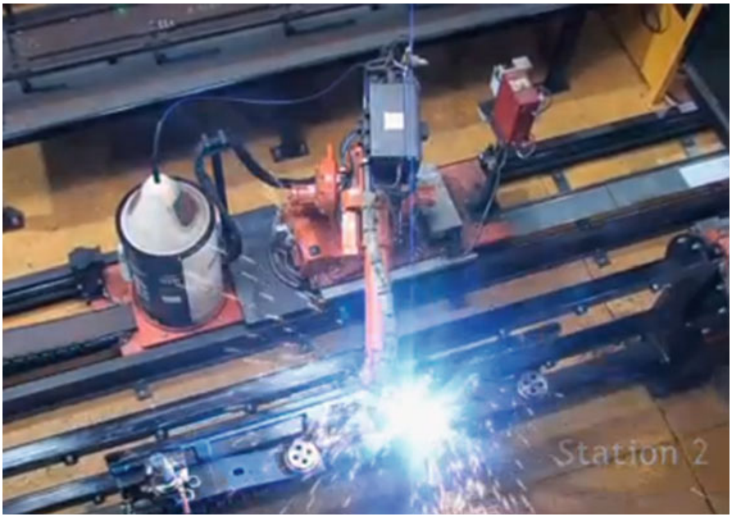

Fig. 13 A track-mounted welding robot

Track-Mounted Robot

A robot welding system with a track-mounted robot offers large working range along the axis of the track. Such configuration, besides the ability to deal with large workpiece, also provides flexibility to cater for a range of workpiece sizes. The most common applications of such configuration are welding of automotive panels, tractor frames, building frames, structural beams, and container panels. Figure 13 is a top view of a welding system where a robot together with wire drum and cleaning station are mounted on a track for welding a long work price.

Gantry-Mounted Robot

Gantry suspends the robot above the workpieces and reaches the welding seams at a different angle from floor-mounted robots. Such configuration allows the robot to move across the workpiece so that wider and taller workpieces can be welded. Long workpieces can be welded if the gantry is mounted on the tracks to form a robotic welding line. Such welding gantry system can be found in shipbuilding industry for panels and ship hull fabrications. One or more robots (Fig. 14) can be mounted on the gantry to achieve high throughput with simultaneously welding.

Column-Mounted Robot

A column can move the robot in a vertical direction so that tall workpieces can be welded. A column may occupy less space on the production floor than the floor-mounted robot with the welding cables being placed in a duct inside the column. The configurations include stationary, travelling, rotary, and rotary cum travelling columns. An example of column-mounted robot is illustrated in Fig. 15.

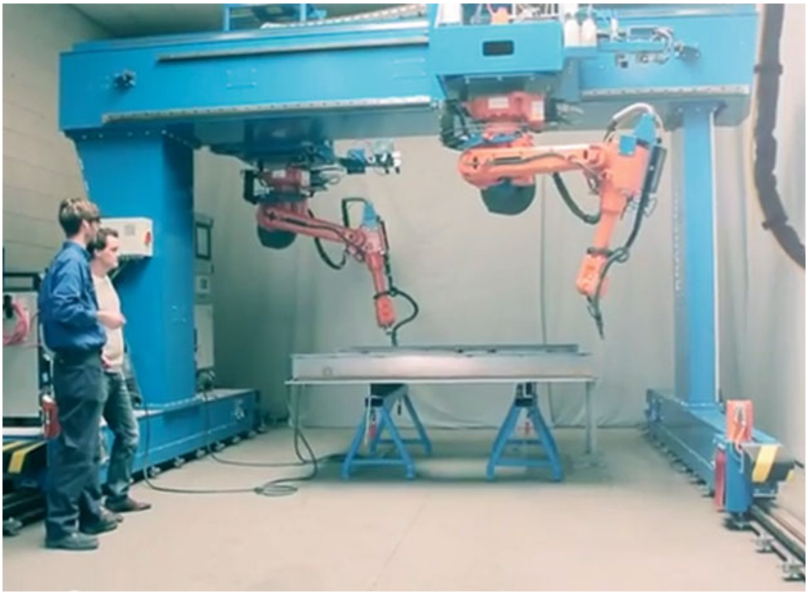

Fig. 14 Two welding robots suspended on a gantry (www.kranendonk.com)

Fig. 15 Column-mounted welding robot (www.igm-group.com)

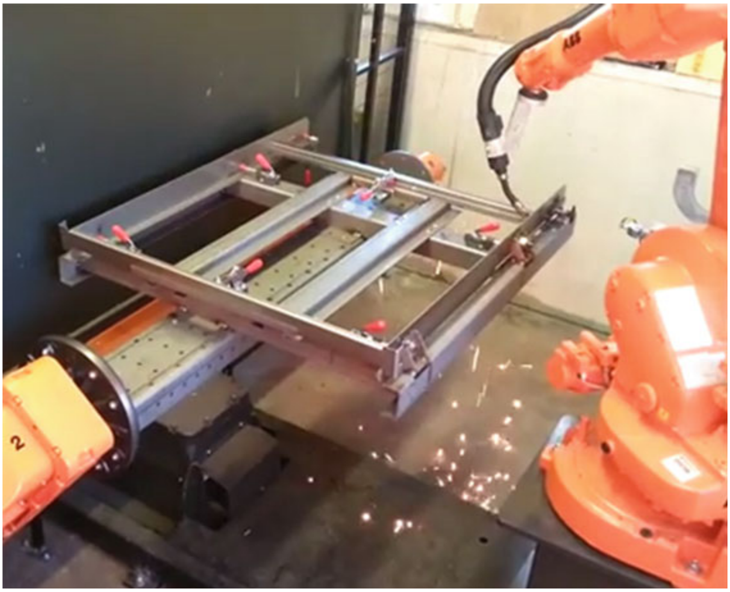

Fig. 16 A frame structure being clamped on positioner

Workpiece Handling System

Workpieces can be either moved or stationary during or between welding operations. Large workpieces or assemblies such as structural steels and beams are placed on the fixture system for a moving robot to access their joints. Smaller workpiece clamped on the fixtures can be orientated by a positioner to provide the best angle for the welding torch.

Fixtures

Fixture is a device that holds the workpiece steadily in place during the welding operation. It is usually fixed on a positioner which may orientate or move the workpiece according to the welding operation needs. The fixture is designed according to the size and configurations of the workpiece, the location of the joints, the type of welding processes, as well as for easy of loading and unloading of the workpiece to maximize the productivity requirements. Further design considerations include protection from spatter, fixture materials selection, welding circuit optimization, simplicity for easy maintenance, and low lost.

A fixture clamps the workpieces at strategic locations to ensure the joints are accurately and steadily presented to the welding robot. A more complex type of fixtures, often called assembly fixtures, holds all loose components of the workpiece together to form the joints. When workpiece is too large or is produced in low volumes, it is preferred the components are pre-tacked before being loaded to the fixture. Figure 16 shows a workpiece clamped on a positioner for welding by the robot.

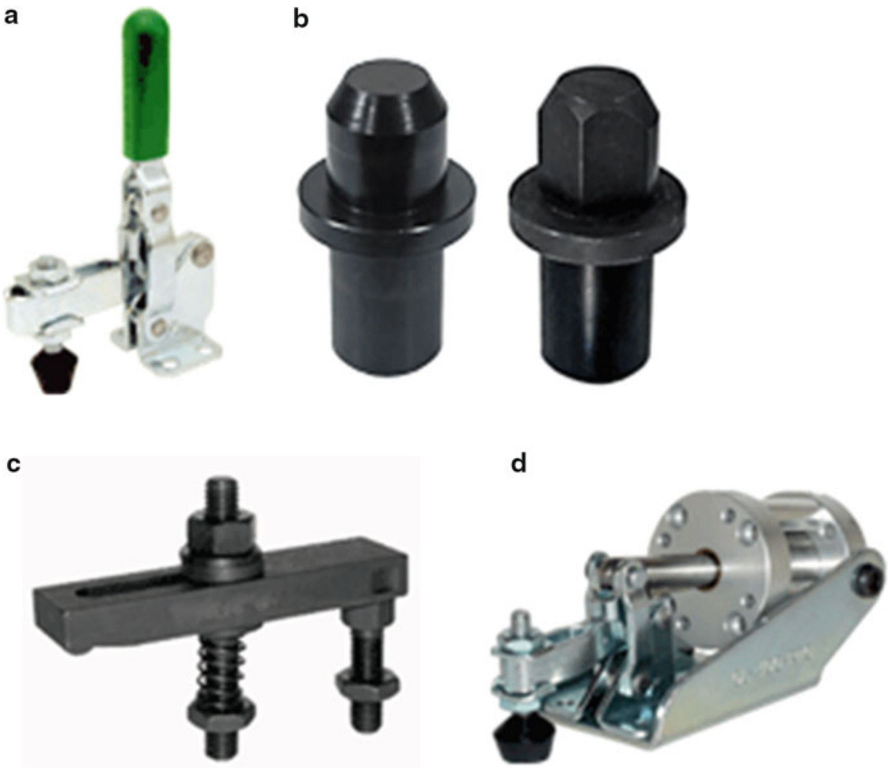

Fig. 17 (**a**) Toggle clamps, (**b**) locating pins, (**c**) clamp straps, (**d**) air-powered clamps

Clamping and Locating Devices

The fixtures come with many types of clamping and locating options for different operation needs. Simple manual clamping such as swing and plunger clamps is typically applied for manual loading/unloading operations for low-volume production. Pneumatic- or electric-driven clamps allow the workpiece to automatically hold the fixtures, which increase productivity with rapid loading and unloading for high-volume production. There are sensors in the fixture to monitor the workpiece presence. More sophisticated sensors such as range sensors are capable to detect the accuracy of the workpiece position. Figure 17 illustrates some commonly used fixture for holding the workpiece.

Workpiece Positioners

Workpiece positioner is one of the most common equipment in the robotic welding system. It moves or orientates the workpiece for the following reasons:

(i) To increase the productivity by simultaneously doing loading/unloading and welding of the workpieces. This can be achieved using a turntable.
(ii) To orientate the workpiece to maximize the deposition rate by coordinating the motion of the robot.

(iii) To turn or roll the workpiece using the turning rolls and idlers to allow the full circumferential welding.
(iv) To allow the robot reach the hard-to-access positions by present the welding points within the work space of the robots using the manipulators.

Depending on the applications, the positioner can be in the form of a turntable, a turn-tilt positioner, and even a six-DoF robot manipulator. The key design considerations of the positioners include the mechanical configuration, degrees of freedom, control types, load carrying capacity, and working environment. Some applications where the workpiece is large and too heavy for any fixture or positioner to handle require the welding robot to provide all the necessary seam accessibility and feed rate accuracy to achieve the quality weld and productivity.

(a) **Turntables**

One of the most common turntables is a horizontal turntable that allows robotic welding at one side while the loading/unloading of the workpiece is on the opposing side. The loading and unloading can be carried out by operator operating outside the work envelope of the robot. A screen divider will safe guide operator from arc flash.

There are several variations of the turntables in terms of rotational axis orientation, types of axis (rotation or linear), and number of axes. Figure 18 illustrates some of the standard configurations of the multi-axis turntable. Customized configuration can be provided to cater for the accessibility of the welding seams in the products. One design feature of all the multi-axis turntables is that all the axes are intersected or nearly intersected at one common point. With that, the workpiece, when moving around the axes, will approximately remain within the work envelope of the welding robot.

Typical specifications of the turntable are as follows: Tilt axis rotation range is about 45º–135º; turntable axis allows full revolutions; and the load capacity of the turntables ranges from a few kilograms up to hundreds tons.

(b) **Handling Robot**

Robot can be used as a workpiece manipulator by working in coordination with one or more welding robots (Fig. 19). This method, often called jig-less robot welding, offers the best possible welding path flexibility by giving access to hard-to-reach seams. It is most cost-effective when a high variety of workpieces are involved since extra jig setups are reduced. The approach also potentially allows the fastest welding cycle time. In selecting the workpiece handling robots and grippers, the key features shown in Table 3 should be considered.

Welding Robots

A robot is programmed to move the welding torch to the weld points or along the weld path in a given orientation, motion pattern, and speed. The robot is typically of

Fig. 18 Workpiece positioners (**a**) turntable positioner, (**b**) Ferris wheel positioner, (**c**) H-frame positioner, (**d**) turn-tilt positioner (www.daihen-usa.com)

the articulated configuration with six DoF to orientate the welding torch according to the requirements of the welding process. Most of the robots currently use AC servomotors with servo-controlled system giving the advantages of high accuracy and maintenance free. Some of the robot arm comes with a hollow duct allowing the welding wire, coolant cable, and power wire to pass to maximize the maneuverability and welding work space.

Robot Arm

The application requirements in terms of the workpiece size, welding process, and operational requirements such as space and cycle time should be considered when selecting the robot. A robot with the proper specifications such as work envelope, degree of freedom, repeatability, payload, weight and mounting limitation will be able to meet the application requirements. Figure 21 shows three typical commercially available robot arms.

Table 4 summarizes typical robot specifications and their impacts to the welding requirements.

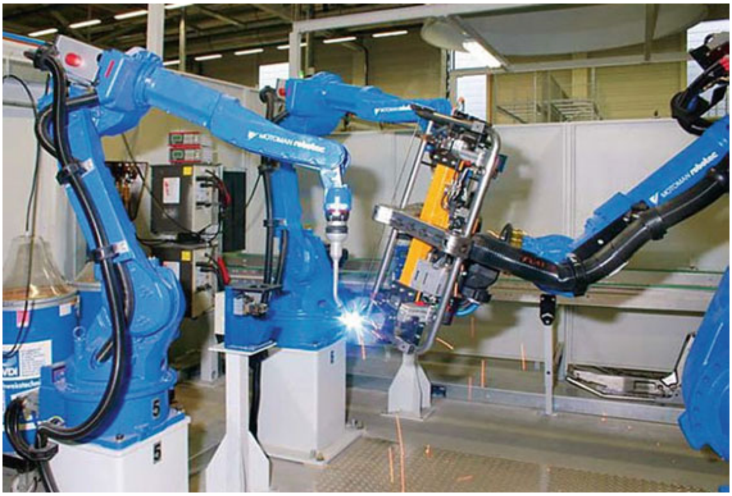

Fig. 19 Robot (*right side*) is holding the workpiece which is being welded by the two robots on the *left side* (www.weldingrobotics.com.uk)

Robot Controller

The robot controller, besides playing the key role in achieving the motion specifications, should be able to cater the needs of the welding process requirements. Advanced robot controllers are able to control additional operational tasks such as workpiece positioning, production sequencing, and worker safety.

One of the main components of the robot controller is the human-machine interface. It is mainly in the form of graphical user interface (GUI). The GUI can appear in the displays of stationary monitor or on a handheld teach pendant. The former allows the off-line programming of the welding robot and the latter lets the operator teach the welding sequence on the workpiece point by point.

Using the GUI interfaces, the operator can teach the robot workpiece position, welding path, and sequence, as well as the welding parameters. Often the workpieces and the welding process information can be obtained from database which has been established prior to repeated operations. Table 5 lists the main functionalities and specifications of robot controllers and their implications to the welding operations.

Welding Equipment

The main component of the welding system is the power source. Compared with manual welding, automatic welding equipment involves additional hardware components such as wire drum, wire feeder, cooling unit, torch cleaner, and welding torch. In addition, the components must have the necessary features and controls to interface with the main control system which is often the robot controller. Figure 22 shows the system configurations of a typical robotic welding system.

Table 3 Features of workpiece handling robots and gripper

Workpiece handling robot	
Robot types	A 6-DoF articulated robot offers the maximum flexibility in manipulating and handling a high variety of different workpieces
Payload	Robots with payload up to 1 tone is available for handling large range of workpieces in different sizes
Controller	One robot controller can be shared by the handling and the welding robot(s) for easy robot programming
Robot gripper	
Gripper actuators	Pneumatic actuated gripper is the most widely used in majority of industrial applications. Such gripper can be activated for opening and closing for gripping a range of object sizes
	Electric actuated gripper is powered by electricity. It has the advantage of controlling the opening size of the gripper and thus providing the highest flexibility in holding a wide range of part sizes and shapes
Multi-finger grippers	Two-finger gripper in general is able to pick parts of simple geometry such as pipes and blocks which has opposing surfaces where the two fingers make contact. A robot gripper with hand-liked capabilities will have three or more fingers for picking complex-shaped objects (Fig. 20). A single such gripper is able to handle different types of parts without using tool changing system
Gripper payload and fingertip force	High payload (up to 10 kg is commercially available) and high fingertip force (up to 40 N) are two important specifications to be considered for the application needs
Overall system design	
Two robots for parts handling	The setup involves two robots with one holding each of the two parts to be welded together. It eliminates the use of any fixed jig thus providing the maximum flexibility
Parts loading and unloading	Parts such as brackets or pipes to be joined to a larger part are arranged manually in predetermined locations in a manner for easy pick-up by the part handling robots. Such setup is generally cost-effective compared with a setup where the smaller parts are randomly placed in a bin. A vision-guided handling robot will pick up the parts for welding on to the larger part

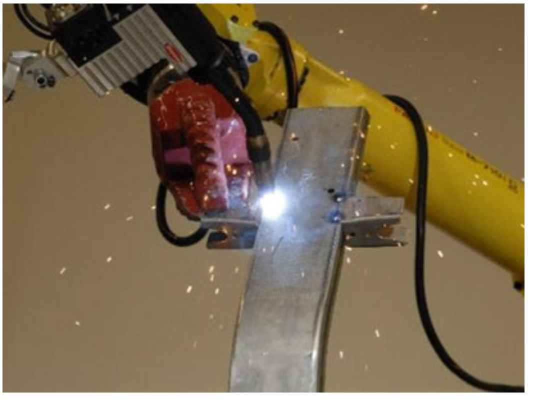

Fig. 20 Robot griping a stamped bracket being welded (Source: Robotiq)

Fig. 21 Welding robot arms, (**a**) robot with a welding power source, (**b**) arm with hollow wrist for cables, (**c**) ceiling mounted robot

Table 4 Typical robot specifications and their impacts to the welding requirements

Items	Typical specifications	Design considerations
Reach	1–2 m	Workpiece size
		Space availability
		Cost
Number of axes (degree of freedom)	Typically six; seven axes robots available	Complexity of workpiece in shapes and grooves
		Range of workpiece types
		Cost
Payload	Around 6–10 kg; up to about 400 kg	Lighter welding torch for arc welding
		Heavy welding tool for spot welding
Repeatability	0.03–0.1 mm	Process welding requirement (multi-passes)
Velocity of tool center point (TCP)	Typically 2 m/s; up to 5 m/s	Welding velocity in general is limited by the welding process rather than the velocity of the robot arm
Robot weight	Around 30–100 kg; up to 300 kg	Moving robot carried by floor track, gantry, or column systems
Mounting position	Upright, inverted, wall or angle mounted	Workpiece size, space for robot
Hollow wrist for cables and hoses	Available specifically for welding robots	Longer-lasting cables and hoses
		Closer to full robot motion performance
Power and signal cables	Life span; flexibility	Physically protected against heat and spatters and interference

Power Sources

The power sources supply the electric power necessary for arc welding processes. Their performance directly determines the weld quality as they are responsible for igniting the arc, allowing stable transfer of the melted electrode material, and generating the amount of spatter.

There are power sources designed for a specific welding method such as GMAW or GTAW as well as those cater for more than one welding methods for wide range

Table 5 Robot controller features and their implications to welding process and operation

Robot controller features	Effect on standard functions	Control for welding process	Control for welding operation
PC based GUI with jog dial	Allow smooth path motion – to provide the required precision in position, orientation, and velocity of the torch for high-quality welding	Fully integrated with the power source to allow optimized welding process execution	Coordinated motion of the workpiece positioner or the transfer system of the robot
64-bit CPU Control of dozens of axes	Allow coordinated and synchronized control of multiple robots and positioners	Welding error handling, production management, and sensor interfacing for seam tracking	Multiple robots synchronization
User I/O more than 20; serial and parallel connections	Ethernet/IP for interfacing with external devices such as welding equipment and seam tracking sensors	Control through-the-arc sensing	Production management and quality control for line production
Common interfaces: Ethernet/IP; Fieldbus such as DeviceNet, Profuse, CC-Link	High-bandwidth communication capabilities – fully integrated with the power source	Monitoring of welding parameters including voltage, current, wire feed speed, and gas flow	Control loading and unloading of workpiece Control the fume extraction hoods
		Monitoring of production results	Control safety screens and doors

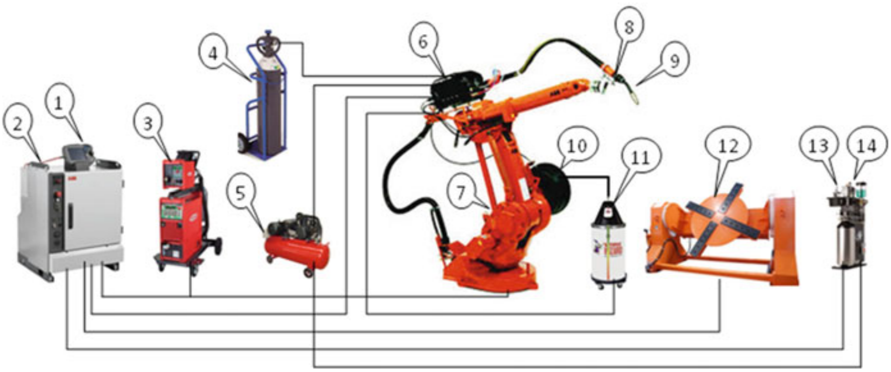

Fig. 22 Welding system configuration: (*1*) teach pendant, (*2*) robot controller, (*3*) welding power source, (*4*) shielding gas cylinder, (*5*) air compressor, (*6*) wire feeder, (*7*) robot, (*8*) clutch, (*9*) welding torch, (*10*) wire spool, (*11*) wire drum, (*12*) workpiece positioner, (*13*) torch cleaning station, (*14*) TCP correction

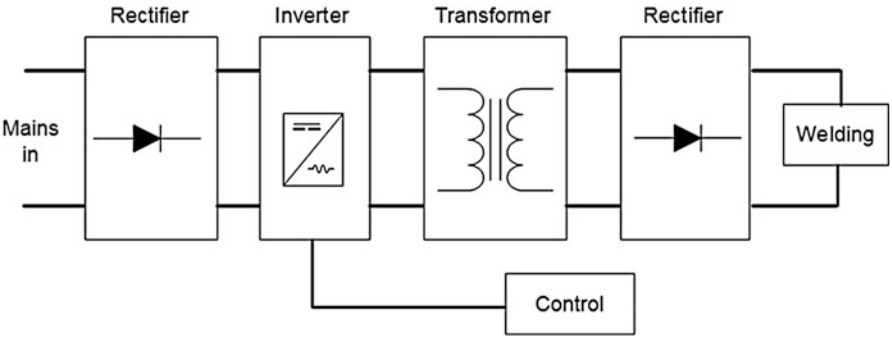

Fig. 23 Schematic of the primary-switched inverter of the power sources

of welding applications. For robotic welding, the power sources used are in general capable to offer most of the welding processes. Such power sources, called multiprocess power sources, allow the user to select among welding processes in GMAW, FCAW, MCAW, and GTAW by changing the accessories and control software. In general, power sources used in automatic welding has a higher duty cycle allowing higher productivity than the manual welding processes.

There are different types of power sources based on how the main supply is converted to the required current and voltage characteristics for the specific welding process. More recent power sources use the rectifier-inverter circuit with power semiconductors making them small in size, lightweight, and low cost. As shown in Fig. 23, in this type of power sources, the incoming AV current is first rectified; then the high-voltage DC output of the rectifier is fed to an inverter which converts the DC to high-frequency AC. The high-voltage and high-frequency AC is reduced by a transformer to a level suitable for welding and finally rectified to produce a DC output. Control is realized by pulse-width modulation.

Typical features of the welding equipment for the different arc welding processes are listed in Table 6.

Welding Torches

The main functions of the welding torch are to direct welding electrode into the arc, conduct current to the electrode, and provide shielding gas to the weld pools.

In the welding torch (Fig. 24a) for GMAW or MIG welding, a contact tube transits the current to the consumable electrode, which is in the form of wire being fed into the welding pool. The torch can also supply the shield gas according to the needs of the welding method. Gas-cooled torch is employed by the process with low current and light duty cycle of up to 60 % while water-cooled is used for heavy duty cycle of up to 100 % and high current. GMAW robotic welding torch may have twin-wire type for higher deposition rate and welding productivity. Both wires are fed to near a single point to give a single weld pool.

The torch (Fig. 24b) used for GTAW welding has a nonconsumable tungsten alloy electrode surrounded by the flow of shielding gas. Torches with welding

Table 6 Features of power sources for different welding processes

	GMAW	FCAW	MCAW	GTAW
Power sources	Single process or multiprocess			
Operation modes	Constant voltage			Constant current
	DC+ (DCEP)			DC- (DCEN)
	DC- (DCEN)			DC+ (DCEP)
				AC
			Synergic	
			Pulsed	
Wire feeder and spool	Electrode (wire) is pull and push with direct current motor			Filler may or may not be used depends on the applications
Electrode	Bare metal wire	Flux-cored wire	Metal-cored wire	Tungsten
Shielding gas supply system	Ar, CO_2, or mixtures of inert and active gases		Argon-CO_2, or Ar-CO_2-O_2	Inner gas (Ar or He) or a mixture of gases
Cooling units	Gas or water cooled depends on the duty cycle and power output			
Welding torch option: escapement to prevent damage in case of collision	Wire comes out from the contact tip			Include the tungsten electrode
	Deliver shield gas			
	Typically water cooled			
	Option: twin wire for higher deposition rate and welding speeds			

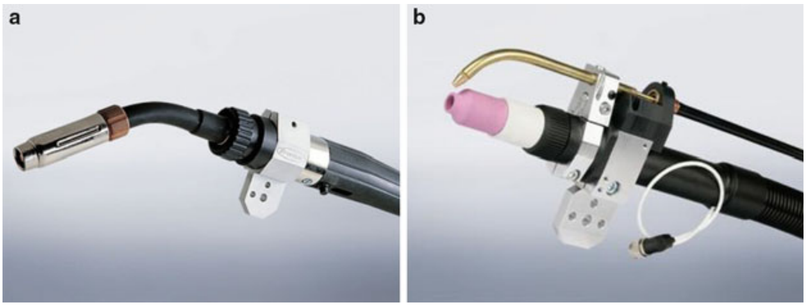

Fig. 24 Welding torch (**a**) GMAW/MIG torch and (**b**) GTAW/TIG torch

current up to 200A are generally gas cooled, while those with above 200A are water cooled with circulating cooling water.

Torches for robotic welding usually come with a bend barrel to provide good access to the workpiece seams. In addition, a collision clutch is employed to prevent damage to the robot arm and the welding torch in the event of a collision.

Fig. 25 Wire feeder mounted on robot arm (www.lincolnelectric.com)

Wire Feeders

Wire feeders add filler metal during robotic welding. They are able to provide the required feed rate for the different welding processes. The wire feeder usually is mounted on the robot arm near the welding torch to have better response time as shown in Fig. 25. It should match to the type of the power source as well as be controllable by the robot controller.

For constant current power source, a voltage-sensing wire feed system is used in which feed rate may be changing continuously, while the constant-voltage scheme requires a constant feed rate during the welding operation. For GTAW welding, the filler wire may not come through the nozzle of the torch. Instead, the filler wire is fed at an offset position into the arc area by a so-called cold wire feeder.

Torch Cleaner and Tip Cutter

The nozzle of the welding torch requires to be cleaned periodically for proper and reliable operation. This is done automatically especially for high duty cycle welding. During cleaning, the torch is moved to the cleaning station where a rotary reamer is inserted into the nozzle. Anti-spatter agent may be sprayed into the nozzle and the stick-out part of the wire is cut to the right length. The cleaning operation is activated at the required interval by the robot controller.

Torch Calibration Unit

It is necessary to regularly confirm the position of the tip of the nozzle which may be shifted due to improper programming of the robot, a collision on the torch, or worn contact tip. The torch calibration is done with the TCP (tool center position) calibration station using the calibration function in the welding programming. The TCP calibration unit (Fig. 26) is normally installed on the torch cleaning station to form a torch service center.

Robot Welding Safety

By replacing the human welder with robots, potential welding hazards are minimized. The potential welding safety hazards include burn, arc radiation, air

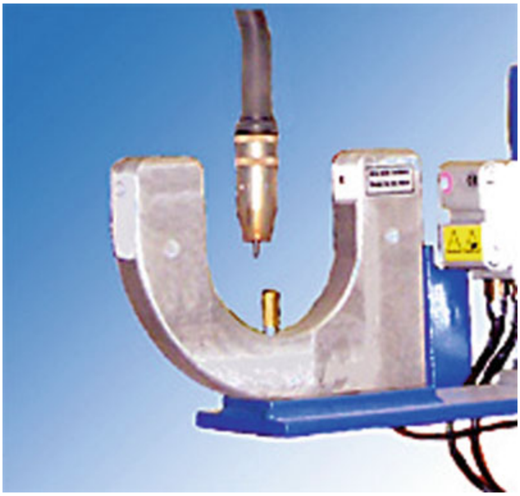

Fig. 26 TCP calibration unit

Table 7 Some relevant safety standards for robotic welding

Standard number	Description
AWS D16.1	Robotic arc welding safety
ANSI Z49.1	Safety in welding, cutting, and allied processes
CAN/CSA-W117.2-06 (R2011)	Safety in welding, cutting, and allied processes
ISO 1021801-1: 2011	Robots and robotic devices – safety requirements for industrial robots – part 1: robots
ISO 1021801-2: 2011	Robots and robotic devices – safety requirements for industrial robots – part 2: robot systems and integration
DIN EN 775	Manipulating industrial robots – safety

contamination, electric shock, fire and explosion, and other hazards. However, robot itself can cause fatal bodily injury. It is advisable that the relevant safety standards are followed during the installation, commissioning, testing, programming, operation, and maintenance stages. Table 7 lists some of the safety standards relevant to robotic welding.

The introduction of robots requires proper safety features in order to protect the operator as well as others working nearby. Each robot installation must be carefully planned from safety viewpoint to eliminate hazards. Barriers may be designed to completely surround the robot welding area to prevent people from entry into the area. All entries must be protected by interlocked doors. Welding curtain may be put up to protect the people from exposure to harmful ultraviolet light and hot spatter. Proper fume extractor should be installed to remove welding fume.

Sensors in Robotic Welding

Welding process is exposed to both geometry and process disturbances. Geometry disturbances are weld joint and path deviations caused by part variation, inaccurate joint preparation, fit-up and alignment error, and thermal distortion. Process disturbances are process parameter shifting due to machine and device tolerances. In manual welding, the welder notices these disturbances and corrects them manually according to strategies learned and gained by experience.

For fully automated robotic welding, these disturbances can be detrimental to both accurate weld path following and welding quality assurance. In order to improve productivity, ensure quality and lower cost for robotic welding operations, sensors are required to provide both geometry and process data for seam tracking and process monitoring. Ultimately, with the sensor feedback, process and motion parameters can be adjusted online to cope with the disturbances.

Advances in sensor and electronics technologies have enabled sensors performance and reliability viable and cost competitive in harsh welding environment. There are a wide range of sensors for geometry detection and process monitoring, even for molten weld pool (Luo and Devanathan 2002), arc radiation (ISF Aachen 2013b), and laser-generated plasma (during laser beam welding) (Luo and Zeng 2002) analysis. The most mature and widely used sensors for industrial applications are those to obtain geometry data and process parameters for weld seam finding and tracking and weld and arc monitoring.

Weld Seam Finding

Weld seam finding is to detect the edge or start of a weld seam. The data can be used for purposes like confirming a product has been loaded correctly, defining a position in space to execute a weld, offsetting a weld seam that varies from batch to batch, and et al. The primary sensors for weld seam finding are tactile (touch) sensing and proximity sensor.

Tactile Sensing

Tactile sensing is a well-established method for weld seam finding. In principle it is a voltage applied to the welding gas nozzle, welding wire or independent probe. The voltage shorts out as it makes contact on the component when touching down in X, Y, or Z plane. The short circuit is recognized by either the robot controller or welding power source, and then corner for the start of a weld or weld edge height can be deduced.

Tactile sensing requires a robot to touch the welding wire or the sensing probe to the workpiece in several places to determine workpiece location and orientation. It is limited to grooves with large dimensions and relatively straight seam path.

Proximity Sensor

Proximity sensor is a noncontact sensor and it operates using an analogue inductive field. The simplest type is a ring coil. If alternating current flows through the coil, a magnetic field is generated. The magnetic field weakens when the coil approaches the workpiece which is metallic and electrically conductive. With multi-coil arrangement in one sensor, the position of the weld groove, as well as the angular and rotational data, can be obtained.

The prominent welding power source manufactures and most mainstream robotic welding system suppliers are all able to provide weld seam finding functionality (Robotics 2012).

Weld Seam Tracking

Weld seam tracking involves weld groove and seam geometry measurement. The measured data allow for not only robot trajectory shifts but also adaptive control through real-time process parameter adjustments to cope with joint geometry disturbances. Weld seam data can be further used for multi-pass welding applications. In multi-pass welding, weld seam tracking is used during root pass. The positional offset data and the parameter adjustment values from the tracked root pass are stored. The stored data can be played back on consecutive passes, which are welded according to a preprogrammed offset from the stored root pass.

There are two main methodologies that can facilitate weld seam tracking. They are laser scanning and through-the-arc sensing, though stereo vision is an alternative option.

Laser Scanning

Laser scanner for seam tracking is based on the principle of laser triangulation. A laser diode projects a visible laser stripe by either laser line projection or laser spot oscillation. The reflected light is received by CMOS or CCD sensors. By detecting changes in the position and shape of the reflection, the position of various points along the weld groove is measured. Thus, Laser scanning provides 2D information of weld width and depth for seam tracking. Figure 27 illustrates the measurement principle of a laser scanner (Juneghani and Noruk 2009).

Technical limitation of laser scanner is its reliability when scanning on highly reflective surfaces. Other considerations need to be reviewed include relatively high cost, maintenance issues due to harsh welding environment, and physical constraints which may limit torch accessibility to the weld joint.

Laser scanning-based seam tracking system has been widely used for both robotic arc and laser welding. One can either work with sensor manufacturers such as SICK, Keyence, Micro-Epsilon, and MEL Mikroelektronik to build weld seam tracker or purchase integrated seam tracking system and software from suppliers like Meta Vision, Servo-Robot, Scan Sonic, OTC Daihen, and Moto Eye etc.

Through-the-Arc Sensing

Through-the-arc sensing requires that the robot weaves across the weld joint during welding. Welding currents are measured during arc weaving to calculate both the

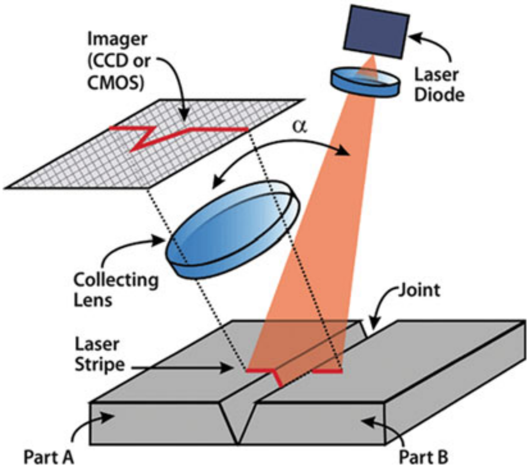

Fig. 27 Schematic illustration of the working principle of a laser scanner (Juneghani and Noruk 2009)

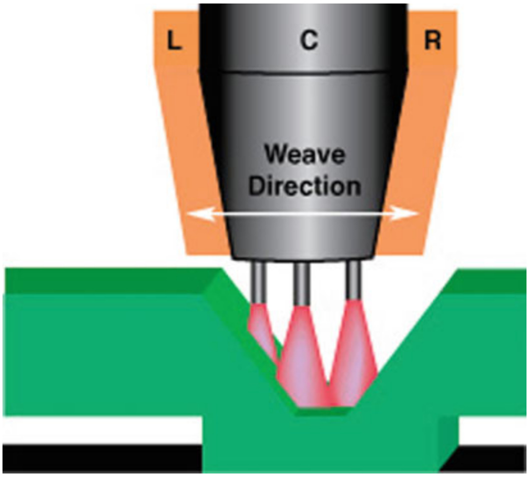

Fig. 28 Arc weaving for through-the-arc sensing (Robotics 2012)

actual seam position and the arc height. These data are then used to adjust the robot's path through lateral and vertical compensation. Through-the-arc sensing is often used in conjunction with tactile sensing. The tactile sensor finds the starting point of the weld. Then, through-the-arc tracking takes over to keep the welding torch in the joint after the arc is struck. Figure 28 illustrates the arc weaving for through-the-arc sensing (Robotics 2012).

Through-the-arc sensing requires no external probes, and all information is gathered through the welding arc itself. It is a very well-proven technology and is very reliable and cost-effective.

The only limitation is the requirement that the robot must superimpose a weave on the weld in order to get the information it needs. Therefore, it is most useful for simple fillet welds or deep groove welds, while its usage for butt and lap welds is limited.

Table 8 Sensors and transducers for welding parameter measurement

Welding parameters	Sensors/transducers
Arc current	Hall effect sensor or current shunt
Arc voltage	Voltage probe
Wire feed speed	Optical tachometer/encoder
Travel speed	Optical tachometer/encoder
Gas flow rate	Calorimeter or gas flow meter
Temperature	Thermal-couple or infrared sensor

Most mainstream robotic welding system suppliers are all able to provide through-the-arc sensing functionality such as ABB WeldGuide, Fanuc ArcTool TAST, and Yaskawa ComArc.

Weld/Arc Data Monitoring

Weld/arc data monitoring refers to the real-time measurement of various welding process parameters. These parameters include arc current, arc voltage, wire feed speed, travel speed, gas flow rate, temperature, and weld time. When welding in pulse mode, pulse parameters like peak and background current and voltage and pulse frequency can also be measured. Various sensors and transducers are used for welding parameter monitoring and some examples are listed in Table 8.

Apart from welding process data, production data like overall equipment effectiveness, downtime, arc-on time, as well as performance factors such as deposition rates, wire use, gas use, and weld faults can also be provided.

With the advancement of database technology, the data acquired can be used for real-time monitoring, arc characteristics evaluation, and production status and trend analysis.

There are both fully integrated and third-party solutions available. Systems fully integrated into the power source are provided by welding power source suppliers like Miller, Lincoln, and Fronius. These systems offer seamless integration and minimal start-up time. Third-party systems are advantageous for major established welding power sources without the option of a built-in solution. Third-party systems can work as a stand-alone unit or can be linked to a PC through Ethernet or USB. They include ARCAgent™ from Impact Engineering Inc., ADM IV™ from Computer Weld Technology, Inc., and ALX II from Partek Laboratories Inc.

Robotic Welding Programming and Software

Robotic Welding Programming Through Application Software Tools

Robots are basically programmed through two methods: teach pendent based online programming and CAD model-based off-line programming. For robotic welding applications, apart from defining weld locations to create robot path, arc welding functions such as setting of torch angle and welding parameters as well as weld

Table 9 Examples of welding application software packages

	ABB	KUKA	Fanuc
Arc welding tool	ArcWelding PowerPac, Virtual Arc, RobotWare Arc	Arc Tech	ArcTool
Spot welding tool	RobotWare Spot	ServoGun	SpotTool
Laser welding tool		LaserTech	
Seam finding and tracking tool	WaveGuide	SenseTech and TouchTech	TAST

seam finding and tracking are also needed. The welding parameters may cover welding, weaving, run-in, burn-back and crater fill schedules, and multi-pass offsets.

Mainstream robot manufacturers all provide welding application software with instructions to realize the abovementioned functions. The welding application software can be used through both online (Ang et al. 1999) and off-line programming environment. Some application software packages examples from ABB, KUKA, and Fanuc are given in Table 9. There are also third-party software packages, such as RobotMaster, CSR from AC&E, and MOSES from AutoCam.

A three-pass robotic welding program created by Fanuc ArcTool is given as an example in Fig. 29. The program includes a main program, a welding program with instructions for arc start and end, setting welding speed, weaving, through-the-arc seam tracking (TAST), and offsetting (root pass memorization (RPM) and multi-pass offset (MP)).

Automatic Robotic Welding Programming

Both online and off-line programming are time-consuming and require robotics knowledge and programming skills. When welding continuously changing designs for flexible operations, these methods are not sufficient. Some efforts have been made to automatically generate welding programs.

One example is RiansWeld^{TM} from Kranedonk Productions Systems (Kranedonk Productions and Automatic Welding 2013; Pan et al. 2011) to completely automate the programming process. The automated programming system has two key low-level modules on which the higher-level algorithms are built upon. They are the robot kinematic model which is used to calculate the various joint angles for a given robot position and orientation and the collision model which determines if the robot components are in collision with the other work cell components. Calculation time is an important consideration for an automated programming system, particularly for the collision model. To check a weld path, the collision model can be run up to 10,000 times for a simple structure or more than one million times, for a complex structure. To accommodate this, the robots in the collision model are represented by a collection of spheres in order to minimize the complexity of the collision calculation.

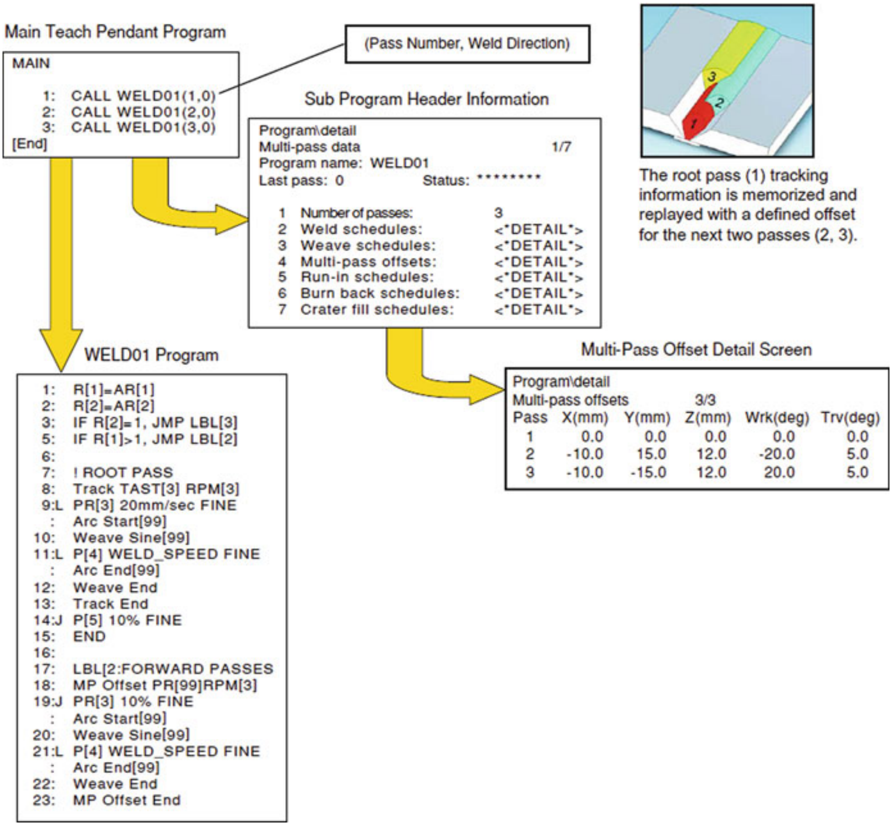

Fig. 29 Robotic welding program using Fanuc ArcTool (Fanuc 2005)

Weld seams are identified by searching for plate edges that align with other plate surfaces. The start and end locations of the intersection edges along with the normal direction to the surface are used for tag placement and orientation. Once the weld tags are generated, calibration points are added along the weld direction and, in the case of a corner, on other required geometries. Linear paths between the weld and calibration points are then checked and optimal robot configuration and external axes position selected. Points are also added using a probabilistic road map (PRM) planner for robot paths that are difficult to access.

RiansWeld™ also links weld geometry with the required weld parameter specification through a database or library of weld parameter settings and path details for many different types of welds and materials.

In summary, the software determines automatically where the welds need to be, how the robots can reach these places, and what parameters should be used for each weld. Currently, RiansWeld™ is mainly used for the welding of complex hull structures and beams. The GUI of RiansWeld™ is shown in Fig. 30.

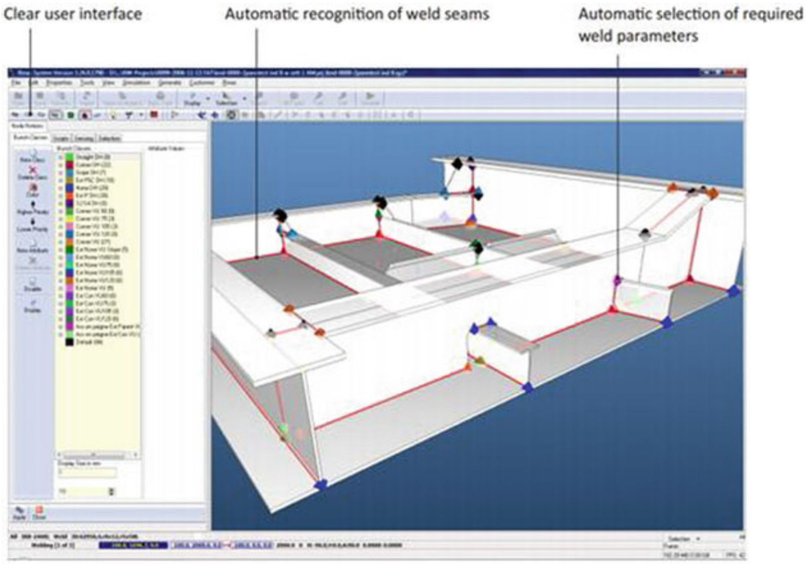

Fig. 30 RiansWeldTM software for automatic robot programming (Kranedonk Productions and Automatic Welding 2013)

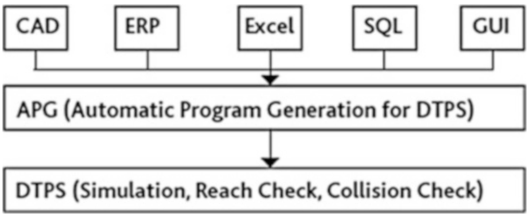

Fig. 31 Automatic robot programming flow through APG and DTPS (Valk 2011)

Another example of automatic robot programming is Automatic Path Generation (APG) on top of the off-line programming software: “Desk Top Programming & Simulation System” (DTPS) for Panasonic robots. It is developed by Valk Welding B. V. (Valk 2011). APG uses data out of CAD systems, ERP, and Excel sheets to automatically generate complete programs for the welding robot, which in addition to the position of the welding torch also contain the torch angle, and the right welding parameters, such as the current, weaving parameters, crater filling parameters, and etc. The path generated by APG is then put into the DTPS for simulation, reach, and collision check. The work flow of APG-based automatic programming is given in Fig. 31.

With APG, it is possible to develop custom-made robot software (CMRS) to program different products automatically within a product family. Successful applications include grid and beam welding for single-piece production and considerable programming time reduction has been achieved.

Table 10 Some of the welding robot suppliers (Source: www.Robotiq.com)

Robot company	Robot models	Suppliers of power sources
ABB	IRB140; IRB1410, IRB1520ID, IRB1600ID, IRB2400-10, IRB2400-16, IRB2600ID-15/1.85; IRB2600ID-8/2.00	Compatible with Miller, Fronius, and SKS
Kuka	KR 5 ARC//KR 5 ARC HA; KR 5-2 ARC HW; KR 16 ARC HW; KR 16 L8-3 ARC HW	Compatible with Lincoln, Miller, Fronius, and SKS
Fanuc	Arc Mate 50iC/5 L, Arc Mate 0iA, Arc Mate 100iC, Arc Mate 100iC/6 L, Arc Mate 120iC, Arc Mate 120iC/10 L, M-710iC/20 L	Packaged with Lincoln welding power source compatible with Miller, Fronius, and SKS
Yaskawa/ Motorman	VA14500, MA1400, MA1800, MA1900, MA3100	Compatible with Miller, Lincoln, Fronius, Thermal Arc, and SKS
Kawasaki	RS05N/L, RS06L, RS10N/L, RS15X, RS20N	Compatible with Lincoln, Miller, Fronius, Kobelco, OTC Daihen, Panasonic, SKS

Table 11 Examples of system integrators for robotic welding

System integrators	Specializations
CLOOS Robotic Welding Inc.	Develop and supply personalized turnkey-automated welding solutions
911 Albion Avenue	
Schaumburg, Illinois 60193	
USA	
Tel: +1 (847) 923-9988	
Fax: +1 (847) 923-9989	
http://cloosrobot.com/	
Kranendonk Production Systems BV	Supply custom-build robotic solutions for wide range of industries including shipbuilding, offshore, transport, structural steels, and process and power
(head office)	
Sir Rowland Hillstraat 10	
P.O. Box 6147, NL-4000 HC	
Tiel, The Netherlands	
Tel: +31 344 623 944	
Fax +31 344 623 388	
info@kranendonk.com	
http://www.kranendonk.com	

(*continued*)

Table 11 (continued)

System integrators	Specializations
OTC DAIHEN, Inc. 1400 Blauser Dr. Tipp City, OH 45371 USA Tel: +1 (937) 667-0800 Fax: +1 (937) 667-0885 www.daihen-usa.com	Manufacture and supply welding equipment (primarily digital inverter welding supplies), cutting equipment, torches, robots, positioning equipment, standard and custom arc welding cells, and accessories
Valk Welding B.V. Staalindustrieweg 15 NL-2952 AT Alblasserdam The Netherlands Tel: +31 78 691 70 11 Fax +31 78 691 95 15 http://www.valkwelding.com	Develop and deliver robotic welding systems, which are intended for flexible production of small to medium-large series
Welding Robotics UK Henlow, Bedfordshire SG16 6EJ United Kingdom Tel: + 44 1462 759025 http://www.weldingrobotics.co.uk/	Manufacture and supply welding equipment (primarily digital inverter welding supplies), cutting equipment, torches, robots, positioning equipment, standard and custom arc welding cells, and accessories

Robotic Welding Suppliers and System Integrators

Most of the major industrial robotic companies manufacture robots for welding applications. They are able to supply the complete robotic welding system including the power sources from the welding power source suppliers. Table 10 lists the robots and their compatible power sources.

There are companies and system integrators who provide the complete welding automation solutions for specific applications. Some of these companies are listed in Table 11.

Summary

This chapter starts with an overview of the welding processes categorizing in terms of fusion welding and solid-state welding. Arc welding, which is one of the fusion welding processes is popularly used in wide range of industries including metal fabrication job shops, construction equipment, construction beams, shipbuilding, and aerospace. Majority of today's robotic systems are catered for the arc welding processes including gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW) processes. Due to the fundamental difference in the welding processes, the welding torches for the two process types cannot be shared but a single welding power source specifically the multiprocess type can be used for both of the processes. Apart from the robot arm and the welding power source, the main peripherals in the robotic welding system are the torch cleaning station, wire feeder, wire pools, and wire drum.

The design considerations for the robotic welding system are the targeted workpiece in terms of material, size, configuration, joint geometry and positions, as well as the production requirements. There are various types of positioners and transfer units for moving the workpiece as well as the robot arm to meet the needs of the workpiece features and operation requirements. For high-mix and low-volume manufacturing featured frequent changing workpiece designs and flexible production, there is automatic robotic welding programming software for setting up the complete robotic welding process and operation. Through-the-arc sensing and advanced add-on optical sensors integrated with optimized welding control in the power source are available to achieve high-quality welds.

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