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Arc Welding Automation

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1. Introduction

It is very well known that the use of robotics in the industry increases productivity and quality in many aspects. It is also well known that some adjustments have to be made to grant payback for the investment and to reach the expected results. Today, the robotization is known as an alternate technique for production, increasing qualitative and quantitative competence of its industries. One point that has been observed in some applications is that inadequate procedure for robot application in welding process reflects in insatisfactory results. These procedures are excessive time expending for implementation, material loss, reworking and poor weld quality.
The main problem detected is that the number of experts in welding "and" robotics is still reduced and some industries are investing in robot without any planning or orientation, believing that the robot will solve all their problems. The results have been disastrous. In many cases even though the weld appearance is acceptable and the welding time is significantly reduced, the weld quality is poor. The experts in robotics know very well what they are doing. However, many of them do not have experience in welding to understand that many features related to welding physics and metallurgy have to be considered when a welding procedure has to be implemented. Because of this, some small and medium industries with large potential for robotization are holding investment and/or postponing it until its adaptation to implement the robot in their production line. It is believed however that very soon many small industries will have their own robot.

2. The paradigm of welding automation

Since the beginning, welding is a process that depends on the welder skills. This relation is so direct that the classification, according to the application methods, is based on the degree of control of the activities related to welding that depends on the human interference. These application methods are classified as manual, semi-automatic, mechanized, automatic, robotic and with adaptive control, according to American Welding Society (AWS).
This classification can be better understood when an agent is established (Table 1) to execute the normal activities involved to realize arc welding (Cary, 1994).
The manual welding is defined, according to the American Welding Society (AWS, 2001) as "welding where the torch or the electrode holder are carried or manipulated by human hands". In other words when the tasks, related with the execution and continuous control of the welding, are made by the hands of the human and are under responsibility of him.

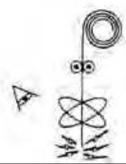
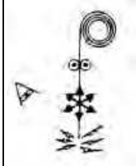
	Manual	Semi-automatic	Mechanized	Automatic	Robotic	Adaptive control
Activities						
Arc start and maintenance	Human	Machine	Machine	Machine	Machine	Machine (with sensor)
Wire feeding	Human	Machine	Machine	Machine	Machine	Machine (with sensor)
Heat control to obtain penetration	Human	Human	Machine	Machine	Machine	Machine (with sensor)
Arc motion along the joint	Human	Human	Machine	Machine	Machine (robot)	Machine (with sensor)
Guide the arc along the joint	Human	Human	Human	Machine (with pre programed track)	Machine (robot)	Machine (with sensor)
Torch manipulation to direct the arc	Human	Human	Human	Machine	Machine (robot)	Machine (with sensor)
Arc corrections to compense erros	Human	Human	Human	Do not occours	Do not occours	Machine (with sensor)

Table 1. Application methods of welding process, adapted from (Welding Handbook, 2001).

Semi-automatic welding is defined as “manual welding with equipment that automatically control one or more welding conditions”. The welder manipulates the torch while the wire/electrode is automatically fed by the machine.

Mechanized welding is defined as “welding with equipment that requires manual adjustments in response to visual observation during welding, with the torch or electrode holder carried by a mechanical system”. The welder participation in this process consist in adjusting the parameters as he observe the operation.

Automatic welding is defined as “welding with equipment that only requires occasional observation and/or no observation of the weld and no manual adjustments”. The function of the welder is only turn the machine on to begin the welding cycle and occasionally check the procedure.

Robotic welding is defined as “welding that is executed and controlled by a robotic equipment”. In robotic welding and automatic welding the function of the welder is to guarantee the weld quality by performing periodic inspections of the results identifying weld discontinuities. When those are find, maintenance and programming must be done to fix such problems.

Welding with adaptive control is defined as “welding with equipment that has a control system that automatically determine changes in welding conditions and act under the equipment with appropriated action to do adjustments”. In this process, sensors are used to detect problems and the controller performs the necessary changes in welding parameters, in real time, to produce sound welds. This type of welding is performed without intervention and supervision of the human.

Accord to the classification presented, the stick electrode welding is a manual process since the welder is responsible for all the activities, while GMAW is a semi-automatic process. This is so because the arc start and maintenance and wire feeding is made by the machine while the torch manipulation is made by the welder. When this manipulation is made by a mechanical device the processes is classified as mechanized.

Independent of the automation degree, its focus is costs reduction by reducing the number of people involved in the production and increasing productivity and quality of the final product by the rational control of the process parameters. An automatic equipment may be projected and programmed to perform a unique task (fix automation) or may be projected for multitasks, by programming, allowing to perform distinct tasks accord with the manufactured product (flexible automation) (Welding Handbook, 2001; Romano, 2002).

In manufacturing area, the term "automation" means that all the functions or steps of an operation are executed or controlled, in sequence, by mechanical and/or electronics devices replacing the human efforts, observation and decision.

The automation involves more than equipments or control by computer and may or may not include charge or discharge of components in an operation. The automation may be partial, with some functions or steps executed manually or may be total, where all the functions or steps are executed by the equipment, in a certain sequence without any adjustment by the operator (Romano, 2002).

To properly classify the automation level of a given process, the first step is to define the activities related to it. The responsible for the execution (execution agent), for the control (control agent) and for the sequence of activities (sequential agent) must be defined. Additionally, it is necessary to define which activities need to be treated as isolated and which must be included in the process operational cycle.

In the arc welding processes, the first activity to execute a weld is to specify which welding procedure must be used. This definition is also known as WPS – Welding Procedure Specification. Considering used material and the weld morphology wanted, the welding parameters related to the process may then be determined. The executor, controller and sequence specification agent of a WPS is the human. Even with a help of a computational program to choose the best parameters or the ones that will be used for the self adjustment of the machine, the final decision for the WPS is the human decision. Between the WPS elaboration and the welding beginning, a time interval for procedure preparation is necessary. Nowadays, this preparation occurs independent of the application method to be used and human direct interference are often necessary.

There is still a lack of a good system to automatically prepare the WPS and, from its preparation, immediately initiate the welding. Of course this system must be universal, since among the parameters to be chosen for the WPS there are the welding processes. It is, however, expected that such activities (WPS and welding start) be treated as isolated activities, because of the human involvement on them. The activities related to the welding cycle, the ones that will define the degree of automation of the process, must be the ones that allows the instantaneous sequence of the process.

The easiest way to relate such activities is to associate them to a welding process. It is unquestionable to say that welding with covered electrode (SMAW) is manual. To start the arc, the welder must approximate the tip of the electrode to the base metal, touch it and slowly and gently pull up such that the arc is established. After, he must translate and feed the electrode, such that the distance between the electrode tip and the weld pool is constant (arc length) until the end. To finish, he must smoothly pull the electrode, getting it apart from the base metal, extinguishing the arc. Spiral movements some times are also used to fill the crater. As observed, in this operation the execution and control agent is the human. All of the described tasks may, however, be made automatic, if needed, not necessarily for productivity improvement, but for security reasons, as hot tapping of tubes and underwater welding. Section 3 shows some results of the robotic SMAW.

According to the classification shown in Table 1, a typical semiautomatic process is the GMAW. To begin the welding, after some preparation, the welder must place the torch close to the base metal and after pushing the trigger, start the wire feeding. As the wire touches the base metal, the arc is established and the welder must translate the torch. As the welder translates it, the machine feeds the wire into the weld pool. To stop the welding, the welder needs only to release the trigger. The machine stops to feed the wire and the arc is extinguished. The arc opening and extinguishing are associated to the wire feeding by the machine (execution agent). However, who decides the feeding start and finishing moment is the human (controller and sequence agent), since he needs to push the trigger.

GMAW is the most suitable arc welding process to be carried by the robot. If the robot substitutes the human welder by translating the torch with a predefined trajectory (been classified as automatic welding according to Table 1), the improvement on repeatability is huge, as the robot will always make the same trajectory. However, to improve the quality, the trajectory needs to be programmed at least as good as the human does it. If the trajectory is not well programmed, the robotic weld will never be better than the human weld. Section 4 shows a case where the trajectory study was crucial to improve the welding quality for the robotic welding.

The execution of torch movement with a mechanical device with mechanical or electronic control (as the robot) is a necessary condition, but no sufficient, to a welding be automatic. In this case, the easiest way to differentiate a mechanized system from an automatic system is to base on the concept of automatic equipment. It is either an equipment designed and programmed to execute an unique task (fix automation) or a flexible equipment that, with reprogramming, allows the performing distinct tasks accord to the product to be manufactured (flexible automation) (Welding Handbook, 2001; Romano, 2002).

An industrial robot is an example of a flexible automatic system. Accord to RIA (Robotic Industries Association), "a robot is a reprogrammable manipulator, multifunctional, projected to move materials, parts, tools and specialized devices by programmed movements to perform many tasks" (Rivin, 1988). The development of this type of machine introduced an elevated degree of flexibility to the production environment.

The main condition for a welding equipment to be robotic is that it should be programmable. The most used industrial robots for welding are the anthropomorphic with six degrees of freedom. They are reprogrammable and multifunctional. This means that these robots may be used to weld different parts, needing only the reprogramming for the new part to be welded.

There are also robots designed for specific tasks. These robots are not multifunctional. A typical case is a robot used for welding, designed to execute an unique type of weld. An example is the robot developed to weld pipelines and will be presented in Section 5. This robot has its movements limited to rotate around the pipe while it stays stopped. Only pipes can be welded with this type of robot. This robot is then called "a dedicated robot".

Finally, to differentiate automatic system from mechanized system is a hard task. This is because the automation may be partial or total and there is not a 100% automatic yet. Regarding to welding systems what can be said is related to a flexible or dedicated (fix) system.

As general rule an automatic process is more productive than a mechanized process which is more than the manual. In welding, the gain in productivity many times is related to the reduction in time with reworking, close arc time and preparation to begin the welding cycle. On the other hand, also as general rule, the cost for implementation increases from manual welding to automatic welding. Allowing to say that one disadvantage of the automatic welding is its initial cost. Detailed studies of economical viability show that the benefits against costs to implement such systems are becoming satisfactory.

In general, if a welding process can be mechanized it can be automatized. The question is when a process should be mechanized and when it should be automatized. Additionally, if this automation needs or not a robot, i.e., it is a fix or a flexible automation.

Many factors must be considered to define the best execution method for a welding process, as type of process, part geometry, weld complexity, amount of welds and desired weld quality.

All these factors must be considered and also the advantages and disadvantages of each method. The more dependable way to define the appropriate method to produce a determined part is studying the economic viability. This should be done because, independent of the automation degree, what is seen is the reduction of manufacturing costs. Using automatic systems this can be reached by reducing the number of people involved in the welding, the increase in productivity and the increase in quality, through the use of more rational process parameters. Also, with automatic systems, the history of the welding and all the preparation also can be stored. This, together with the repeatability, allows the traceability of welded parts.

The following sections show some examples of welding automation in different levels for different applications.

3. Robotic shielded metal arc welding

One of the main problems with the shielded metal arc welding process is the bead weld quality, related to its microstructure homogeneity and its physical and dimensional aspect. These factors are directly related to the fact of such process to be, currently and predominantly manual and even the best welder is incapable to weld with absolute repeatability all the weld beads. This process mechanization already exists and increases the repeatability. However it has limits with bead geometry, which is determined by the mechanism assembly. In Figure 1 is shown a device which uses gravity to move the electrode holder (a) along a fixed trajectory (b) as the electrode (c) is melted.

There are many applications for the manual SMAW process but two of them are more specific and there is no other process that can be used. One application is underwater welding, as shown in Figure 2. For a long time many tries have been made to replace coated electrode in this type of welding, without success. It is easy, versatile and the chemical control of the weld metal is the most acceptable. Another application is hot tapping of tubes as shown in Figure 3. In this application, the welder has to weld a tap tube to the main line with inflammable fluids passing inside. As the main line cannot be emptied, this is a dangerous procedure to the welder, however it is the only way acceptable nowadays.

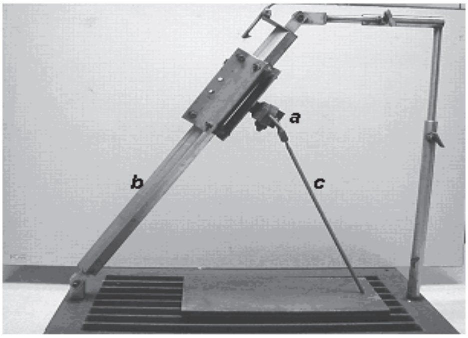


Fig. 1. Device used for gravity welding with covered electrode.

Fig. 2. Underwater welding with SMAW.

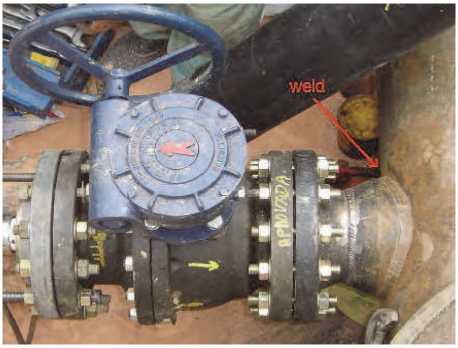


Fig. 3. Hot tapping with SMAW.

Aiming the improvement of the weld quality allied to the repeatability proportionated by the mechanization and the manual process flexibility, the process robotization appears as a solution. However, the robotization brings the problem that, depending on the electrode diameter and the weld current, the melting rate is not constant during all the electrode length. This is because the welding current crosses all the electrode length, causing its heating by Joule effect. This heating facilitates the melting of the electrode, which increases as the electrode is consumed. Thus, if the weld is made using a constant feed speed, it will obtain a bead with non homogeneous dimensional characteristics (Bracarense, 1994). Its morphology (width and reinforcement) increases as the material is deposited, since the melting rate, and consequently the material deposition rate increases as the weld is performed. Experimental results (Oliveira, 2000) had shown that, beyond of getting an irregular bead and without penetration, a constant feed speed can cause the electric arc extinction just after the beginning of the weld.

3.1 Trajectory generation

Due to this melting rate variation, this welding process cannot be programmed with the simple teaching of an initial and a final point to the electrode holder, as in this case it would be obtained a constant feed speed. Moreover, it is not possible to precisely calculate, before starting the welding, the melting rate behavior, as it depends on a number of process variables, as the electrode temperature, welding current, air flow etc.

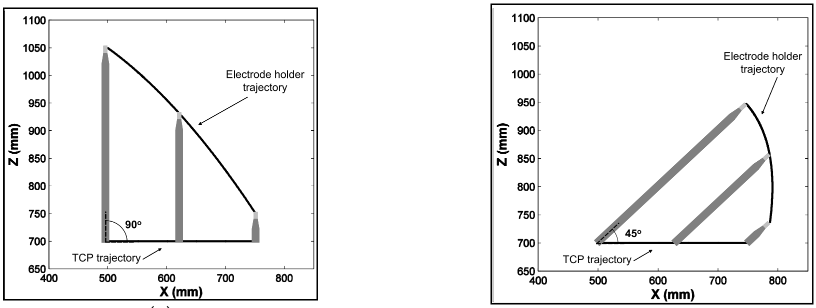
So, to robotize the shielded metal arc welding, it is not sufficient to follow a predefined trajectory over the groove, as in the GMAW and FCAW processes, in which the wire feeding is automatic. In SMAW, it is necessary to make the feeding movement, in order to maintain constant the electric arc length. As the melting rate is not constant, the feeding speed has to be regulated during execution time.

The methodology presented by Lima II and Bracarense (2009) allows the Tool Center Point (TCP) movement programming in a similar way as in GMAW and FCAW, in a transparent way to the user. So, it is only necessary to program the weld bead geometry or trajectory over the groove without caring about the electrode melting.

The electrode is considered as a prismatic joint of the robot. Considering the joint length given by the electrode length, the TCP moves on the programmed trajectory and, at each sampling period, the new joint displacement is calculated and updated in the robot kinematics model. So, the diving movement of the electrode-holder is made independently of the welding movement.

Considering the initial and final electrode holder positions shown in Figure 4 and melting rate experimentally obtained by Batana and Bracarense (1998), Figure 5(a) shows the TCP and electrode holder trajectories during welding. The electrode tip moves along predetermined trajectory while the electrode holder makes the diving movement. In this case, as the electrode is parallel to the Z_0 axis, the electrode holder diving movement is made in this direction, as it moves in X_0 direction. The independence among the TCP advance movement and the electrode holder diving movement is easily stated. However, considering now a welding angle of 45^o, these movements are not independent (Figure 5(b).

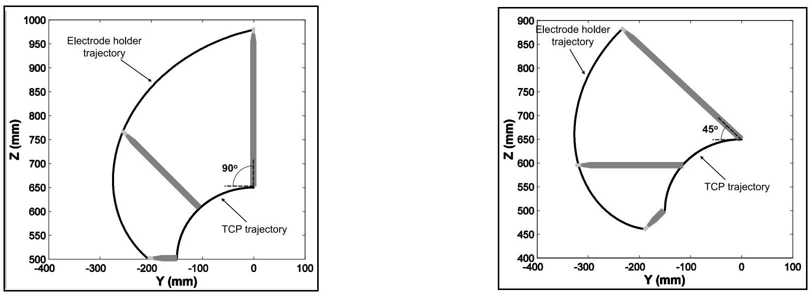
Fig. 4. Initial (a) and final (b) robot positions during shielded metal arc welding for a 90^o welding angle.



(a) (b)

Fig. 5. Tool Center Point and electrode holder trajectories for welding angles of (a) 90º and (b) 45º.

This methodology can be extended to non linear trajectories, as in the orbital welding or welding for hot tapping in pipelines. The operator only has to program the welding trajectory in the same way as it is done in welding processes with continuous wire feeding. Figure 6(a) shows the programmed TCP trajectory on the tube and the electrode holder trajectory for 90º of welding angle and Figure 6(b) shows those trajectories for 45º of welding angle. More complex welding trajectories may be programmed by using a sequence of linear and circular movements as in other welding processes.



(a) (b)

Fig. 6. Tool Center Point and electrode holder trajectories for 90º (a) and 45º (b) welding angles in orbital welding.

3.2 Electric arc length control

Previous works (Oliveira (2000); Batana & Bracarense (1998); Quinn et al. (1997)) seeking the robotization of the welding process with covered electrodes suggested the development of models for electrode melting rate considering current and temperature, to determine the speed of the electrode holder diving. Thus, making the diving movement at speeds equal to the melting rate, the arc length should remain constant throughout the welding. However, imperfections in the models, errors in current and in temperature measurements and other disturbances cause small differences between the value of the calculated melting rate and real melting rate. These differences, even if small, can cause great variation in the arc length, since it depends on the integral of the instantaneous difference. This shows that an "open loop control", as used by Oliveira (2000) is not suitable for the system.

The solution used here is to make a measurement of the arc length to determine the diving speed and use it in a "closed loop controller". In this case, a reference value for the arc length is given and the error is calculated as the difference between the reference and the actual arc length measured from the electric arc.
One solution for the problem of measuring the arc length would be to measure the voltage in electric arc (V_{arc}), since they are directly related. In the process a constant current power source is used. The problem is that it is not possible to directly measure the arc voltage, because, during welding, the electrode tip, near the melting front, is not accessible. It is possible, however, to measure the voltage supplied by the power source (V_{source}) through the entire electrical circuit, as shown in Figure 7, which includes the voltage drop in the cable, in the holder, in the base metal ($V_{c1}+V_{c2}$) and, mainly, along the extension, not yet melted, of the electrode, V_{electr}.

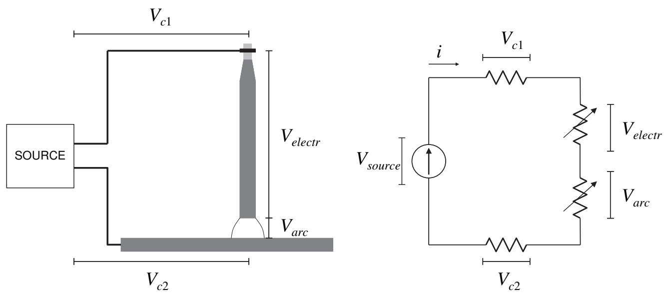


Fig. 7. Electrical circuit of covered electrode welding

It may be considered that the sum of the voltage drop in the cable, in the electrode holder and in the base metal ($V_{c1}+V_{c2}$) are constant along the welding since the welding current is kept constant by the power source. However, the voltage drop along the electrode that has not yet been melted, V_{electr}, is not constant, due to the reduction on its length and due to the increase of its electrical resistivity with temperature. Thus, even if the controller keeps the V_{source} constant through the control of the diving speed, it does not guarantee that V_{arc} is constant throughout the process, which does not guarantee, therefore, a constant arc length.
In this study, a model of the electrode voltage drop, as a function of temperature to compensate for the effect of its variation was used.
The electrode voltage drop V_{electr}, may then be modeled as:

$$V_{electr} = \rho(T)\frac{l_{electr}(t)}{A} I \ , \qquad (1)$$

where ρ(T) is the electrode electrical resistivity as a function of temperature, $l_{electr}(t)$ is the electrode length not yet melted, A is the area of the electrode wire and I is the welding current. As the electrical conductivity of the core wire is two orders of magnitude greater than the coating (Waszink & Piena, 1985), one can consider only the resistivity and cross sectional area of it.
As the electrical resistivity ρ of the core wire material varies with its temperature, it is important to know the temperature behavior along the electrode during the process. In Felizardo (2003) the authors conclude that the longitudinal temperature profile along the covered electrode is practically constant. Its heating is due to the Joule effect caused by the

high electric current crossing the electrode. The conduction of the heat generated by the electric arc to the electrode is often slower than the fusion rate, which causes the temperature to be constant along the electrode length. Then, temperature can be measured during welding using thermocouples (Dantas et al., 2005) placed under the coating near the electrode holder.

3.3 Results

To validate the methodology, an anthropomorphic industrial robot, with 6 rotational degrees of freedom was used. This robot uses a controller that allows programming from simple, linear and circular join-to-joint movements to creation of complex programs, including changes of parameters at run time (KUKA, 2003). These characteristics make possible the implementation of the proposed methodology for trajectory generation and control of the electric arc length during welding. To perform data acquisition, a modular system I/O-SYSTEM 750 from WAGO® was used. This system communicates with the robot controller by a *DeviceNet* interface. For the tests, a constant current power source, capable to supplying currents up to 250A, and an open circuit voltage of 70V was used. A drill chuck was used as electrode holder (Dantas et al., 2005). The supply current is made through the jaw of the chuck, which is in turn electrically isolated from de holder by a part of nylon. To enable the arc initiation in the welding start point, it was used a composite specially developed to burn when submitted to electric current (Pessoa et al., 2003). When the composite is burned, the arc is established and the robot starts the movement. At the end point the current is interrupted by a fast movement of the electrode and the arc is terminated.
Using the robot routines to define tools, the Tool Center Point models with the complete electrode and with the melted electrode were defined (Figure 8).

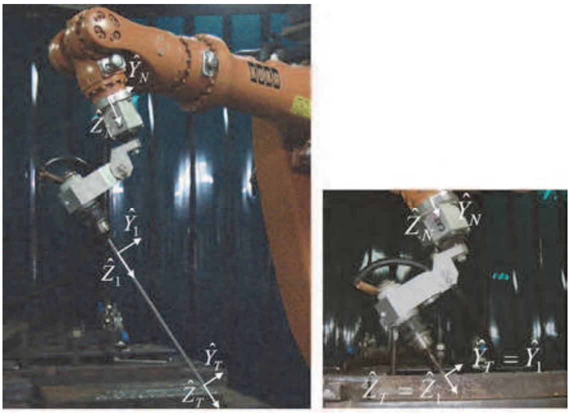


Fig. 8. Complete electrode and melted electrode frames.

The proposed methodology allows welding with covered electrode of any length, diameter and type of coating, since it performs the closed loop control of the process. Thus, the proposed methodology was validated with rutile type covered electrodes (E6013) of 4mm in diameter, and with basic type covered electrodes (E7018) of 3.25 mm diameter. The welding current ranged between 150A to 180A as indicated by the manufacturer. Plates and tubes of carbon steel were used for linear and non-linear (circumferential) welding trajectories.

During the process, it was possible to observe that although the robot can keep the mean voltage constant, the arc length increases significantly at the end of the weld, as discussed above. To compensate this effect, the model of the electrode voltage drop in function of its length and temperature was used to correct the feedback signal used by the controller. For this, tests were made to obtain the curve of temperature versus time. Thermocouples type K were used for monitoring temperature during welding (Dantas et al., 2005).
Welding tests were then made using this compensation. The reference voltage (V_{ref}) was set to 21V. Figure 9 shows the voltage on the electrode (V_{electr}) as a function of time. Despite the voltage drop compensation in the electrode varies of only 0.5V, it was observed that the length of the arc remained constant throughout the execution of the weld, reinforcing the need for such compensation.

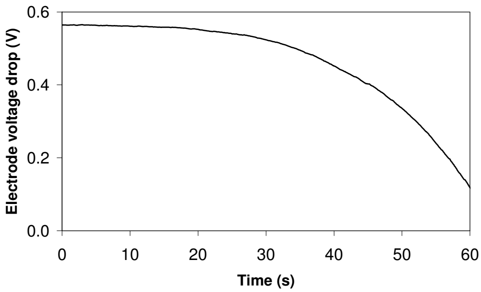


Fig. 9. Electrode voltage drop during welding.

To prove the repeatability achieved with the automation of the process, several beads on plate were performed using the E6013 electrodes with 4mm diameter, welding current of 175A, reference voltage of 21V and welding speed of 2.5 mm/s. Figure 10 shows the appearance of the welds. Despite the spatter problem it is possible to observe that all the welds are identical, demonstrating the repeatability obtained with the robotization of the process.

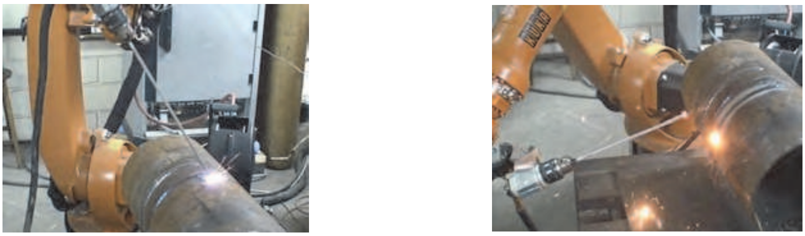
Fig. 10. Beads on plate performed by the robot using E6013 electrodes, demonstrating the repeatability of the process.

Aiming to demonstrate the flexibility of the used methodology with respect to the variety of electrodes, tests were made using E7018 electrodes of 3.25 mm in diameter. The best welds were obtained using current of 150A, speed of 2.5 mm/s and the reference voltage of 26.5 V. Figure 11 shows the appearance of welds.

Fig. 11. Welds made using E7018 electrodes demonstrating the flexibility and repeatability of the process.

As can be observed, the welds are more uniform and with less spatter than the ones obtained with E6013 electrodes. It is important to note that the E7018 electrodes, despite producing best quality welds, have greater difficulty in manual welding. In the experiments, however, these electrodes did not present any operational difficulties in relation to E6013 electrodes, but was necessary to conduct some additional experiments to adjust the reference voltage as the voltage of the electric arc varies considerably with the change of the electrode coating.

To demonstrate the generality of the developed methodology for the trajectories generation, an orbital welding on a steel tube with 14 inches diameter was conducted. The welding started in the flat position, going downward in vertical position with the electrode in an angle of 45º, pulling the weld bead. E7018 electrodes were used with a current of 130A, welding speed of 5.5 mm/s and reference voltage of 18V. Figure 12 shows robot positioned with the electrode at the arc opening and after its extinction.



(a) (b)

Fig. 12. Robot positioning (a) before arc opening and (b) after arc extinction.

Fig. 13. Welds made on tube with E7018 electrodes.

Figure 13 shows the appearance of two welds made on the pipe with the same welding parameters, demonstrating the repeatability of the process.
The results show that is possible to automate an intrinsic manual process, bringing reliability and repeatability to it. Also it can be applied when the task is dangerous to be performed by the human welder.

4. Robotic GMAW

Before deciding for the automatization of a process using welding robots, various factors such as definition of the goals to be reached (production volume increase or quality improvement), necessity of improvement in the adjustment between the parts, among many factors must be verified (Bracarense et al., 2002).
This section shows the cooperation between University and Industry in the welding of scaffolds used in civil construction. The company wanted to use robots to improve the production, but was in doubt about the weld beads quality and the economic viability. The production line of scaffolds used manual welding and did not control the welding sequence nor the deposition rates. The University was then contacted to study the viability of using a robot to carry through these operations.

4.1 Scaffold welding study

Among many scaffold types manufactured by the company, the tubular scaffold was the one studied. These scaffolds are manufactured in three different models, with 1,0m by 1,0m, 1,0m by 1,5m and 1,0m by 2,0m, as shown in Figure 14.

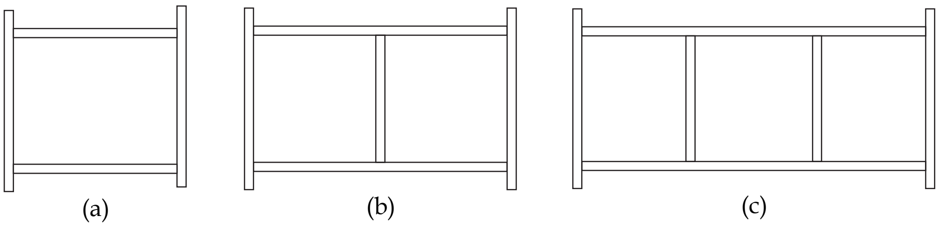
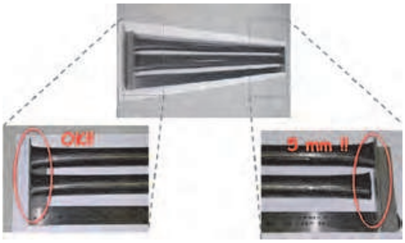
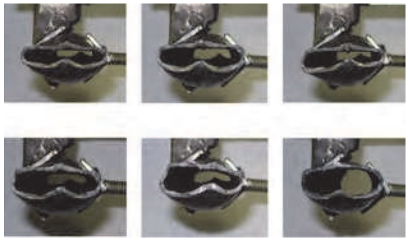


Fig. 14. Scaffold models manufactured by the company: 1,0m x 1,0m (a), 1,0m x 1,5m (b) and 1,0m x 2,0m (c).

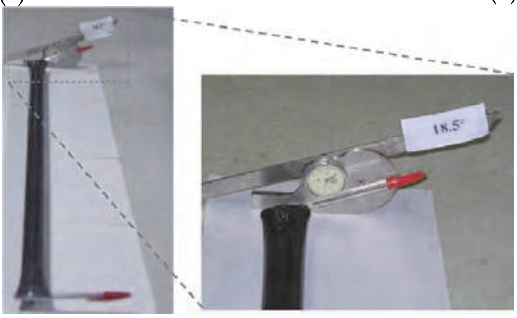
In the manual process, before the welding, the scaffold joints are arc spot welded using Shielded Metal Arc Welding. Two operators work in this procedure: while one places the tubes on a jig, the other spot welds the joints in other jig. A great variation in the arc spot welding times is observed. For an average of 39,6s for arc spot welding of a complete scaffold, a standard deviation of 11,1s was obtained (Pereira & Bracarense, 2002).
Initially some problems, such as differences in tubes lengths (Figure 15a) and cut finishing (Figure 15b), beyond lack of parallelism in its extremities (Figure 15c) have been stated. These problems would compromise the robotic welding, since, although the manual welder perceives such differences and compensates them during the welding, the robot is not capable to make it, as its movements are based on a previous programming. To make possible using the robot, some modifications had been carried through in the cutting process in order to minimize such problems.



(a)



(b)



(c)

Fig. 15. Problems in the tubes preparation: difference in length (a), difference in the extremity sections (b) and lack of parallelism (c).

Aiming to define the size of the robot to be specified, simulations had been done using commercial software (Figure 16). The scaffold of 1,0m x 2,0m was considered in this simulation, because its bigger dimensions among the others to be produced. A MOTOMAN SK6 robot was considered the model since it was the one to be used in the laboratory.

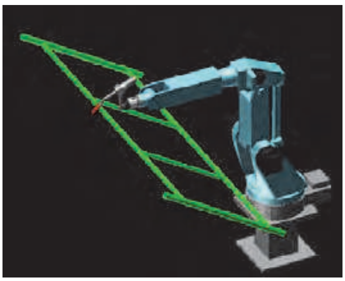


Fig. 16. Computer simulation of scaffold welding process.

The use of a simulation software allowed, beyond verifying if all the joints to be welded would be inside of the workspace of the robot, to verify if it would be possible to locate the tool with desired orientation in all the points to be welded, that is, if all the points would be inside of the robot dexterous workspace (Craig, 1989).
Then some welds had been carried through in the laboratory at the University within the objective to study the best welding parameters to be used (Figure 17).

Fig. 17. Tests at University laboratory for verification of the welding parameters.

Through tensile test, it was verified that the welds made using the robot are stronger than those manually welded (Pereira and Bracarense, 2002). Additionally, it was verified that the rupture occurs far from the HAZ (Heat Affected Zone), confirming the higher quality of the welds made by the robot. It was also stated that there was not any visible modification in the weld bead after the tests. Accepting the viability of using robots for the scaffold welding, the company decided to acquire a robotic welding cell.

4.2 Robotic cell conception and development

The Company acquired a KUKA KR16 robot, similar to MOTOMAN SK6, but with a wider workspace. The layout of the cell, projected by the University, consists of three jigs located around the robot (Figure 18). In this cell the operators can mount or remove two scaffold while the robot welds another in the third jig.

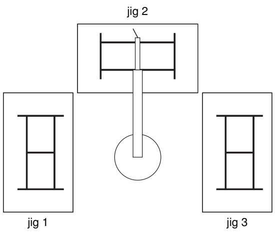


Fig. 18. Robotic cell conception.

The construction and installation of the robotic cell was supervised by the University and carried through the Company, which has resources to produce doors, gratings, tables and jigs (Figure 19).

Fig. 19. Installed robotic cell.

As it was conceived, with three jigs, the robotic cell allows getting a work cycle of practically 100%. Considering that the robotic arc spot welding process is faster than the manual scaffold assembly, it is possible to the robot to weld two scaffolds while two operators remove the welded scaffold and assembly new ones in the two other jigs.

4.3 Arc spot welding program development

Considering the problems observed in the tubes preparation, it was opted to initiate programming the arc spot welding of the scaffold to posterior manual welding by the operators. An operator would be trained on the robot programming and would follow the development of the arc spot welding program. This operator would be also responsible for determining changes in the cutting process, guiding the other employees to adapt it to the robot.

As commented before, the arc spot welding was originally made manually using SMAW. With the robot, the arc spot welding would be made with GMAW (Gas Metal Arc Welding), being, therefore, unnecessary to remove the slag after arc spotting, before welding of the joints.

The 1,0m x 1,5m scaffold has 6 joints to be welded. The complete arc spot welding consists on 12 spots with approximately 10mm, being 2 spots on each joint, as shown in Figure 20.

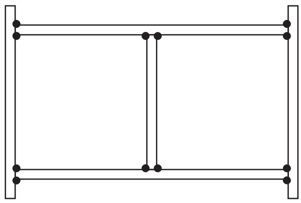


Fig. 20. Points to be arc spot welded in 1,0 x 1,5m scaffold.

To program each spot, it was identified two positions (one oscillation) for the robot program (Figure 21). The electric arc is opened in position 1, moves to position 2 and extinguish the electric arc.

Fig. 21. Positions used to program each arc spot welding: position 1 (a) and position 2 (b).

However, due to differences in the tubes lengths and lack of parallelism in the cuts, still present in its preparation, it was not possible to obtain a good repeatability in the spot welding. In some points occurred lack of fusion, being necessary manual rework.

It was opted then to program the arc spot welding using 3 oscillations with the torch moving twice to each position: after opening the electric arc, the robot would move from position 1 to position 2, back to position 1 and, finally, back to position 2, extinguishing the

electric arc. This way, it was possible to almost get a utilization of 100% in welds, although the lack of repeatability in the preparation of the tubes.
With this procedure, the arc spot welding program with 12 welds lasts on average 55 seconds. Considering three operators doing assembly of scaffolds on the jigs, the robot was capable to arc spot weld 520 scaffold per day.

4.4 Program optimization

This program, although efficient, was not productive, as the human operators are capable to arc spot weld the same number of scaffolds in less time. It was then performed a study to optimize the robot programming aiming to reduce the time cycle, without compromise the arc spot quality.
Initially, it was opted to reduce the number of torch movements on each spot, from three to two oscillations. To avoid problems caused by differences on the tubes, it was necessary to adjust the weld parameters, increasing the voltage, keeping the current constant, to increase the bead width without increasing the heat input.
Some tests were done to verify the arc spots quality, resulting in satisfactory joints (Figure 22). Even using only two torch oscillations, it was obtained almost 100% of good welds.

Fig. 22. Arc spot welded joint.

The average cycle time was reduced to 47 seconds, resulting in a daily production of 610 scaffolds.
Considering that this number was still low, it was opted to develop a new configuration of arc spot welds. In this case, instead of using two spots on each joint, the program was changed to make two spots in the inner joints and only one spot in the outer ones, as shown in Figure 23. This way, the number of arc spots to be make in each joint decreased from 12 to 8 spots.

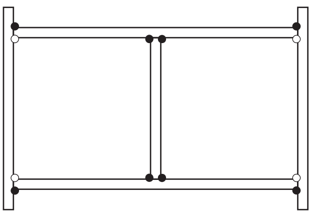


Fig. 23 Arc spot welds configuration using only one spot in the outer joints.

Figure 24 shows a spot in one of the outer joints.

Fig. 24. Outer joint spot.

The average cycle time was reduced to 31 second, resulting in a daily production of 920 scaffolds, over the company expectation that was of 900 scaffolds per day. However, those scaffolds presented a low flexural stiffness resistance, which could cause deformations during the transport and posterior welding.
It was then used a new spots configuration, in which the inner joints have only one weld spot, while the outer ones have one or two, alternatively, as shown in Figure 25. The average cycle time was not changed as the number of spots is also 8, maintaining a daily production of 920 scaffolds.

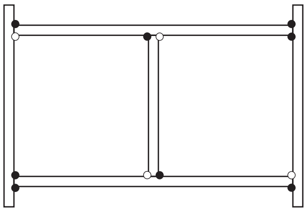


Fig. 25. Arc spot welds configuration to increase flexural stuffiness resistance using only 8 spots.

Figure 26 shows an arc spot weld made in one inner joint. It was observed a significant increase in the flexural stiffness resistance. However, it was still lesser than using 12 arc spot welds. It was then used a new configuration, as shown in Figure 27. This new configuration, in theory, would increase the resistance as it locates the isolated spots in points with less flexor moment.

Fig. 26. Weld spot in one inner joint.

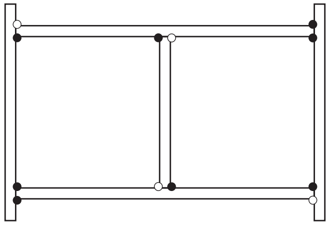


Fig. 27. Alternative configuration of arc spots to increase flexural stiffness resistance using 8 spots.

As foreseen the new configuration produces scaffolds with a greater stiffness resistance, if compared to the previous configuration.
The next step was to program the complete welds; however, the repeatability of the tubes preparation was not adequate to the robotic welding process. Some tests showed that it is possible to weld tubes with joints with almost 3mm of gap by changing the welding parameters in order to obtain wider beads (Fig. 28a); however, if the gap is greater than this value, it is not possible to obtain adequate beads (Fig. 28b).

(a)

(b)

Fig. 28. Weld obtained changing welding parameters for small gaps (a) and great gaps (b).

This work shows that a robotic system is not always able to solve practical problems, as its programs just repeat the previously programmed trajectory and parameters. To solve this problem it would be necessary an adaptive control system to measure the gap and change welding parameter for each joint.

5. Development of a robot for orbital welding

Manufacturing of oil and gas lines is made through the union of metallic pipes, which length, in average, changes from 12 to 14 meters, in order to produce lengthier ducts. Figure 29 shows pictures obtained in a pipe work performed in Brazil. Figure 30 shows the welding procedure. The process used to weld these pipes is called circular or orbital welding. As can be seen in the figure, in Brazil the welding of pipes is all manually carried through with the GTAW process (Gas Tungsten Arc Welding) and coated electrode - SMAW (Shielded Metal Arc Welding).
The manual welding is not just ergonomically improper to the human been because the pipes are welded in loco and near to the floor but also it does not guarantee the desired productivity and repeatability. The great challenge then was the development of a robot for the orbital welding of pipes aiming to better comply the work with requirements. This process has as operational characteristic the fact that each welding bead is composed by 4

different welding positions. The positions are the plain position, the over-head position, the ascending vertical position and the vertical descendant position. In each one of them the optimal welding parameters are different and a robot must to self adjust to them.

Fig. 29. Preparation of a pipeline assembly. (a) pipes positioning and (b) root pass.

Fig. 30. Pipeline manual welding procedure.

As commented before, the definition of a robot is a "reprogrammable multifunctional manipulator designed to move materials, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks". From this definition, it can be said that the devices for the orbital welding shown in literature up to now (Blackman and Dorling 1999; Yapp and Blackman 2004) are not robots, because they do not allow the programming of trajectories or parameters of welding. For these reasons, it is said that the currently process of orbital welding is mechanized, not robotic.

Weld pipes *in loco* using anthropomorphous industrial robots would be possible, however impracticable, due to the great weight which would have to be dislocated to each new pipeline bead. The device developed and that will be presented here, in such a way, makes possible the programming of trajectories, so as programming the welding parameters for the orbital welding of pipes. Therefore, such device can be called a robot due to its capability of being completely programmable and automatically carrying through all welding activities: opening and closing the electric arc, moving the welding torch (controlling the welding speed, the torch angle and stick-out) and controlling the welding current and the electric arc voltage. However, incapable of being completely multi-functional (it could not be used for a generic task, being limited to movements around of the pipe), such mechanism can be defined as a "robot designed to special tasks".

The development of the welding started with some tests been performed by a qualified welder using GMAW and FCAW processes in order to obtain optimal orbital welding

parameters (Soragi, 2004). Beads on pipe were made in the four welding positions – flat, overhead, vertical up and vertical down. For every sample produced, metallographic tests were performed to determine the bead quality and the best welding parameters. An anthropomorphous industrial robot was also used to check the repeatability and weld quality in the four positions.
From the obtained results, best parameter tables were generated indicating the optimal parameters (voltage, current, welding speed, torch angle and stick-out) for each welding position mainly with tubular wire. In the intersection or where the welding changes from one position to other the parameters were interpolated in a small interval to avoid discontinuities and heterogeneity of the bead.
It was observed, however, that the optimal parameters for the descendant vertical welding substantially differ from those at vertical up, flat and overhead. Choosing to weld all around the pipe would introduce then unnecessary difficulties in the regions where the parameters must change from one position to other. It was opted then to perform welding only in the following sequence: overhead, vertical up and flat. Thus, the robot must weld one side of the pipe, extinguish the arc, go down to the other side and perform the other bead in the same sequence. This, of course, has the inconvenience of having electric arc extinguished. However, it allowed using short cables to connect the robot to the controller and to the welding machine.
In order to change parameters during the welding process, it was necessary to know the position of the robot in relation to the flat position. This positioning can be provided by a sensor that informs the inclination where the robotic system is at every moment (the inclinometer).
The robot was projected and constructed with 4 degrees of freedom: movement around the pipe, torch angle, stick out and torch lateral motion. Figure 31 shows these 4 degrees. As the robot has to weld pipes near the floor, it needs to be compact. Many versions were studied. Figure 32 shows the first and the 6th version.

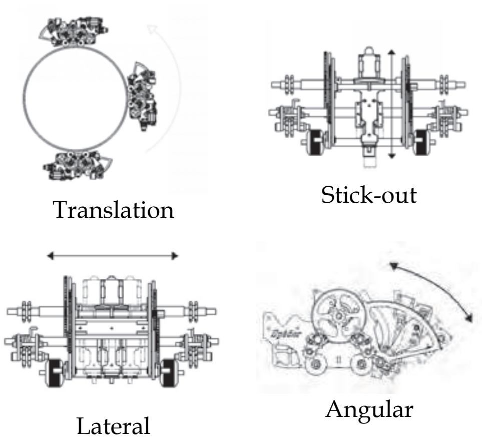


Fig. 31. Degrees of freedom of the robot.

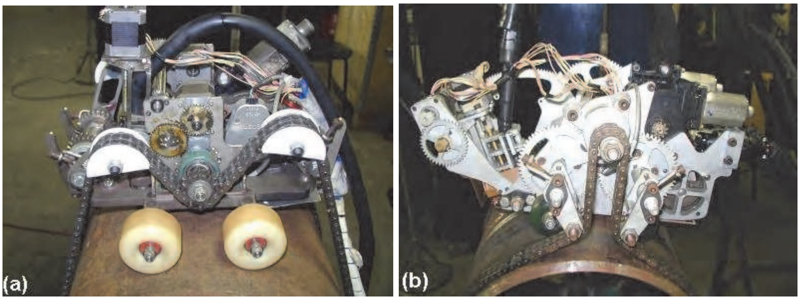


Fig. 32. Versions of the robot (a) the first and (b) the 6th.

In order to drive the movement around the pipe and to control its speed, a DC motor was selected, driven by PWM (Pulse Width Modulation). For the stick out, inclination and lateral motion it have been selected step motors which although its reduced dimensions, provide high torque. Moreover, for these movements, position control must be precise, what makes the step motors the perfect choice. The robot controller is implemented in a PC in which digital output and input boards were added in order to make possible to drive and control the robot axles, as well as the welding machine. During the program execution, the controller generates set point values to the speed of the first axle and position of the three following axles. The values of welding speed, the torch angle and stick out are informed through the parameters look-up table. Thus, for each position of the robot around the pipe (which is read from the inclinometer sensor), it is possible to generate the set points with the optimal values for such parameters.

Knowing the reference values, the controller implements the speed control of the movement around the pipe. The speed measuring is performed by means of an encoder located in the axle of the driving motor. Using the encoder pulses frequency, the real speed of the robot is determined with precision. When some error between the reference and the real speed exists, the driving voltage of the driving motor is modified so that the error heads to zero. After calculating the new driving voltage, an analogical signal is generated through a D/A board and sent to the PWM which amplifies the signal power and drives the DC motor.

In the case of this robot, the controller must be as robust as possible, as many factors have influence in the system dynamics: the traction in the chains, the robot position (flat, overhead, descendant vertical and ascendant vertical), the pipe diameter etc. On the other hand, in the positioning control of the step motors are used drivers that feed the coils in the right order, so as to put them into motion according to the signal sent by the PC.

The conventional welding source was modified in order to have two independent wire feeders allowing simultaneous use of two robots. Originally, the weld font had a potentiometer to adjust the welding voltage. Each one of the feeders has a potentiometer to adjust the welding current (wire feeding speed). Both potentiometers were manual. So, the operator would have to regulate voltage and current before starting the welding.

To the robotic process, however, it is needed that the welding parameters (current and voltage) be regulated by the robot itself. Thus, an electronic board was developed to work as the interface between the robot controller and the welding machine. The values of current and voltage to be used are determined by means of the parameters look-up table, in accordance to the robot position around the pipe. The digital values for regulation of the welding font are determined by means of a calibration curve from the welding power source.

Figure 33 shows a weld bead made by the robot. It can be observed the homogeneity of the bead, even where the welding position is modified. This is achieved by the gradual variation of the parameters of the table during the welding.

Fig. 33. Weld bead.

The orbital welding process robotization brings enhancement in the final product quality, considerable increase of the repeatability, reduction of rework and reduction of the weld execution time. At the very least, the robot is capable to reproduce the work (the weld bead) of the best human welder, through the use of the same parameters contained in a reference table. Moreover, it is possible to optimize such parameters, in order to increase the quality and to reduce the weld execution time through the welding speed increase.
The use of the robot in the welding with GMAW and FCAW revealed to be extremely viable. It was shown that the bead aspect did not suffer great variations from a welding position to another one, if a gradual change of the parameters (voltage, current, welding speed, torch angle and stick-out) is executed. In pipes with larger diameters, it is still possible to use two robots simultaneously, decreasing even more the closed arc time, which consequently increases the work factor.

6. Conclusions

This chapter discussed the many levels of automation of the arc welding processes, from the manual process (with no automation) to the adaptive control. To implement the automation of a process and to decide which level should be implemented, some aspects need to be studied as financial viability and number and variability of welds. If it is an extremely variable process, it should be considered no automation at all, as the setup and programming would take more time than the welding itself. On the other side, if it is a repetitive process with an adequate preparation of the parts to be welded, a robotic system with a preprogrammed task would guarantee repeatability and productivity to the process.

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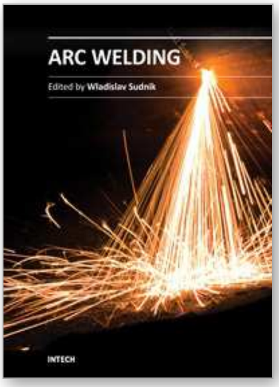

Arc Welding

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Ever since the invention of arc technology in 1870s and its early use for welding lead during the manufacture of lead-acid batteries, advances in arc welding throughout the twentieth and twenty-first centuries have seen this form of processing applied to a range of industries and progress to become one of the most effective techniques in metals and alloys joining. The objective of this book is to introduce relatively established methodologies and techniques which have been studied, developed and applied in industries or researches. State-of-the-art development aimed at improving technologies will be presented covering topics such as weldability, technology, automation, modelling, and measurement. This book also seeks to provide effective solutions to various applications for engineers and researchers who are interested in arc material processing. This book is divided into 4 independent sections corresponding to recent advances in this field.