Robotic Shielded Metal Arc Welding

A methodology was developed for robotic welding with SMAW covered electrodes using a variation of the tool center point

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ABSTRACT

In this work, the development and validation of a methodology for robotic welding with covered electrodes (SMAW) using a variation of the tool center point (TCP) model is shown. The covered electrode becomes part of the kinematic model of the robot as an additional prismatic joint, whose movement is determined by the electrode consumption or melting rate. This allows programming the trajectory to be welded similarly to welding processes with continuous wire feeding (GMAW or FCAW). In these processes, the points of beginning and end of each section of the trajectory are defined by the programmer and the robot performs, by default, the predefined trajectory of the TCP between these points, while the wire is fed independently of the robot movement.

The robot performs feeding of the covered electrode through a diving movement while carrying out the advance movement along the trajectory. A closed loop mesh controls the length of the electric arc using the measurement of the voltage supplied by the welding machine. This compensates for the variation in the electrode voltage drop due to its length and temperature in order to maintain the arc length constant throughout the weld.

Introduction

Despite being extensively used and being especially suited for applications such as underwater welding and hot tapping in gas and oil pipelines, the shielded metal arc welding (SMAW) process, using covered electrodes, has been avoided for some applications due to a possible lack of weld quality with regard to microstructure homogeneity, physical appearance, and size. These factors are directly related to the fact that this process is, currently, predominantly manual, and the welder is unable to perform all the welds exactly equal. It should be also considered that underwater and hot tapping applications are dangerous for humans to perform. Mechanization of the process already exists and helps to increase the repeatability; however, there are limitations regarding the weld geometry, which is determined by the mechanism.

Aiming at improving the safety and weld quality together with repeatability provided by mechanization while maintaining the flexibility of the manual process, the robotization of the process (Ref. 1) appears as a possible solution. So, the process could be performed by a submarine robot in the underwater welding or by a mobile industrial robot for hot tapping. In the case of repair welding, the presented methodology may be used in association with a joint tracking or vision system for automatic groove identification.

However, with robotization, the problem is the melting rate of the covered electrode is not constant throughout the welding execution, depending on the electrode diameter and welding current. This is due to the fact that the welding current crosses the entire length of the electrode that has not yet melted, heating it by Joule effect. This heat, in a direct way, facilitates the fusion of the electrode, which increases its fusion rate. Thus, if the welding is performed with constant dive speed, the weld will come out with nondimensional homogeneous characteristics (Ref. 2), since the melting rate, and consequently, the deposition rate along the weld, increase. Experimental results (Ref. 3) showed that, in addition to obtaining an irregular weld without complete penetration, a constant diving speed can lead to arc extinction in a short time after the start of welding.

This work shows development and validation of the robotization of the welding process with covered electrode. Presented are a literature review of previous research with the ultimate goal of automatizing the process, the proposed methodology for the generation of trajectories to control the length of the electric arc, implementation of the proposed methodology in an industrial robot, and the results of the robotization of the process.

Bibliographic Review

Kang (Ref. 4) shows the development of a tool to mechanize underwater welding with SMAW. Because with this type of welding it is difficult for the welder to maintain a constant arc length, the weld beads usually have irregular aspects. Based on the arc voltage control (AVC), the mechanism regulates the electrode feeding speed according to the voltage measured between the electrode holder and the base metal, while the welder moves the holder along the welding path. This approach does not consider, however, variations in the electrode electrical resistivity due to the increase of temperature by Joule effect. This causes incorrect measurement of the electric arc voltage, since there are voltage drops along the electrode length.

Oliveira (Ref. 3) shows the design of a robot with two degrees of freedom that performs, respectively, the translational and diving movements of the electrode. The use of this robot allows variations in diving speed in order to offset the effects of increasing temperature, considering the models obtained in Batana and Bracarense (Ref. 1). However, Oliveira’s methodology considers the open loop control of the arc length, using as diving speed the value of the fusion rate obtained through mathematical models. Therefore, it does not guarantee a homogeneous weld, since there is no guarantee that the...
length of the electric arc remains constant.

The present work uses a closed loop control and proposes use of a model of the voltage drop on the covered electrode according to its length and temperature. This obtains a more precise measurement of the electric arc voltage for use as feedback to the robot controller, guaranteeing weld bead uniformity.

**Methodology**

**Trajectory Generation in Robotic Shielded Metal Arc Welding**

In shielded metal arc welding, it is not sufficient to follow a predefined trajectory over the groove, as in the gas metal arc (GMA) and flux cored arc (FCA) processes, where wire feeding is automatic. In SMAW, it is necessary to make the feeding movement in order to maintain a constant arc length. As the melting rate is not constant due to the heating caused by the Joule effect, feeding speed has to be regulated during execution.

The methodology used (Ref. 5) allows programming of tool center point (TCP) movement in a similar way as in GMAW and FCAW, in a way transparent 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 here 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, a new joint displacement is calculated and updated in the robot kinematics model. Therefore, the diving movement of the electrode holder is independent of the welding movement.

Figure 1 shows a model for the electrode holder for robotic SMAW with attached frames.

The frame \( N \) or the last joint frame of the robot may be determined considering \( C \) as an intermediate frame, located at the completed consumed electrode and \( T \) as the TCP frame. Then,

\[
\begin{align*}
0^N_T &= 0^R_C T \\
0^N_T &= 0^R_N T
\end{align*}
\]

such that \( ^R_T \) represents the prismatic joint associated with the electrode. The kinematic model to compute the TCP position is given by

\[
\begin{align*}
\theta^N_T &= \theta^N R T \\
\theta^N_T &= \theta^N R N T^3
\end{align*}
\]

and the robot joint positions may be calculated using the inverse kinematics model applied to the matrix \( ^R_T \).

Considering the initial and final electrode holder positions shown in Fig. 2 and the melting rate experimentally obtained by Batana (Ref. 6), Fig. 3A shows the TCP and electrode holder trajectories during welding. The electrode tip moves along a predetermined trajectory while the electrode holder makes the diving movement.

As the electrode is parallel to the Z axis, the electrode holder diving movement is made in this direction as it moves in the X direction. In this case, the independence of the TCP advance movement and the electrode holder diving movement is easily stated. However, considering now a welding angle of 45 deg, these movements are not independent — Fig. 3B.

This methodology can be extended to nonlinear trajectories, as in orbital welding or for hot tapping in pipelines. The operator only has to program the welding trajectory in the same way as is done for welding processes with continuous wire feeding. Figure 4A shows the pro-
grammed TCP trajectory on the tube and the electrode holder trajectory for a 90-deg welding angle; Fig. 4B shows those trajectories for a 45-deg welding angle. More complex welding trajectories may be programmed using a sequence of linear and circular movements as in other welding processes.

Electric Arc Length Control

Previous works (Refs. 3, 6, 7) seeking robotization of the welding process with covered electrodes suggested development of models for electrode melting rate that considered current and temperature to determine the speed of the electrode holder diving. Thus, when making the diving movement at speeds equal to the melting rate, the arc length should remain constant throughout welding. However, imperfections in the models, errors in current and temperature measurements, and other disturbances cause small differences between the value of the calculated melting rate and the real melting rate. These differences, even if small, can cause great variations 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 (Ref. 3), 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 calculated as the difference between the reference and the measured length from the electric arc.

One solution for the problem of measuring the arc length is to measure the voltage in the electric arc ($V_{\text{arc}}$), 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 ($V_{\text{source}}$) through the entire electrical circuit, as shown in Fig. 5, which includes the voltage drop in the cable, holder, base metal ($V_{c1} + V_{c2}$) and, mainly, along the extension, not yet melted, of the electrode, $V_{\text{electr}}$.

It may be considered that the sum of the voltage drops in the cable, electrode holder, and base metal ($V_{c1} + V_{c2}$) are constant along the weld since the power source keeps the welding current constant. However, the voltage drop along the electrode that has not yet been melted, $V_{\text{electr}}$, is not constant, due to the reduction of its length and the increase in its electrical resistivity with temperature. Thus, even if the controller keeps the $V_{\text{source}}$ constant through control of the diving speed, it does not guarantee that $V_{\text{arc}}$
is constant throughout the process, and therefore does not guarantee 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, $V_{\text{electr}}$, may then be modeled as

$$V_{\text{electr}} = \rho(T) \left( \frac{l_{\text{electr}}(t)}{A} I \right)$$

where $\rho(T)$ is the electrode electrical resistivity as a function of temperature, $l_{\text{electr}}(t)$ is the electrode length not yet melted, $A$ is the area of the electrode wire, and $I$ is the welding current. Since the electrical conductivity of the core wire is two orders of magnitude greater than the coating (Ref. 8), one can consider only the resistivity and its cross-sectional area. As the electrical resistivity $\rho$ of the core wire material varies with its temperature, it is important to know the temperature behavior along the electrode during the process. In Ref. 9, 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 electrical current crossing the electrode. Conduction of the heat the electric arc generates 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 (Ref. 10) placed under the coating near the electrode holder.

**Equipment and Materials**

To validate the methodology, an anthropomorphic industrial robot, with six rotational degrees of freedom was used. The robot uses a controller that allows programming from simple linear, circular, and joint-to-joint movements to creation of complex programs, including changes of parameters at run time (Ref. 11). These characteristics make possible implementation of the proposed methodology for trajectory generation and control of the electric arc length during welding. To perform data acquisition, a modular I/O-SYSTEM 750 was used that communicates with the robot controller through a DeviceNet interface. For the tests, a constant-current power source, capable of supplying currents up to 250 A and an open circuit voltage of 70 V was used. A drill chuck was used as the electrode holder (Ref. 10). The supply current is made through the jaw of the chuck, which is in turn electrically isolated from the holder by a piece of nylon. To enable arc initiation at the welding start point, a composite specially developed to burn when submitted to the electric current (Ref. 12) was used. When the composite is burned, the arc is established and the robot starts moving. At the end point, a quick movement of the electrode interrupts the electrode and terminates the arc.
Using the robot routines to define tools, the TCP models with the complete electrode and with the melted electrode were defined — Fig. 6.

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

Results

To control the electrode diving speed, a proportional and integral (PI) controller was used. The derivative action was dismissed due to large fluctuations in the electric arc voltage caused by gas movement, stirring of the weld pool, and transfer, as described in ter Berg and Larigaldie (Ref. 13). Figure 7 shows the closed loop system, where $V_{ref}$ is the reference voltage, $e$ is the control error, $l_{elect}$ is the electrode length, $v_d$ is the diving speed the robot provides, and $V_{source}$ is the voltage measured between the welding source terminals.

The PI controller is used to determine the new value for $l_{elect}$ at each sample period to be used in the kinematics model of the robot (Equation 3). As the transform matrices are updated, the robot makes the diving movement ($v_d$), making the error ($e = V_{ref} - V_{source}$) as small as possible.

Figure 8 shows the measurement of the electric arc voltage during welding using the initial controller values ($K_p = 20$ and $K_i = 7$) and the values after the PI controller tuning ($K_p = 40$ and $K_i = 5.5$). The reference value for the voltage is $V_{ref} = 25$ V.

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 previously. To compensate for this effect, the model of the electrode voltage drop in function of its length and temperature was used to correct the feedback signal the controller uses, as described previously. For this, tests were made to obtain the curve of temperature vs. time. Type K thermocouples were used for monitoring temperature during welding (Ref. 10).

Welding tests were then made using this compensation. The reference voltage ($V_{ref}$) was set to 21 V. Figure 9 shows the voltage on the electrode ($V_{elect}$) as a function of time. Despite the voltage drop compensation in the electrode varies of only 0.5 V, it was observed that the length of the arc remained constant throughout the execution of the weld, reinforcing the need for such compensation.

To prove the repeatability achieved with automating the process, several beads on plate were performed using 4-mm-diameter E6013 electrodes, 175-A welding current, 21-V reference voltage, and 2.5 mm/s welding speed. 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.

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

As can be observed, the welds were more uniform, with less spatter than those obtained with E6013 electrodes. It is important to note that the E7018 electrodes, despite producing better quality welds, are more difficult to use in manual welding. In the experiments, however, these electrodes did not present any operational difficulties in relation to E6013 electrodes, but it 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 generating the trajectories, orbital welding on a 14-in.-diameter steel tube was conducted. The welding started in the flat position, going downward in a vertical position with the electrode at an angle of 45 deg, pulling
the weld bead. E7018 electrodes were used with a current of 130 A, welding speed of 5.5 mm/s, and reference voltage of 18 V. Figure 12 shows the robot positioned with the electrode at the arc opening and after its extinction.

Figure 13 shows the appearance of two welds made on the pipe with the same welding parameters, demonstrating the repeatability of the process.

Conclusions

This work presents the robotization of the welding process with covered electrodes, combining the flexibility of the process and the repeatability and safety of the automation. A methodology was developed to generate the electrode holder trajectory during welding in order to move the weld bead forward along the base metal with the welding speed and angle programmed by the operator, keeping the electric arc length constant. The arc length is controlled using a closed loop feedback controller of the arc voltage.

To avoid increasing the electric arc along the weld, an effect that occurs when considering the arc voltage as the measured voltage in the power source terminals, a model for electrode voltage drop, allowing a more precise determination of electric arc voltage value was developed and used. The model for the electrode voltage drop should take into account its consumption.

The use of an industrial robot with a flexible programming interface allowed the programming of the generation during execution time of the electrode holder trajectory and calculation of electrode consumption.

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References


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