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REAL TIME TRAJECTORY GENERATION IN ROBOTIC SHIELDED METAL ARC WELDING

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Abstract. *The Shielded Metal Arc Welding (SMAW) is a typical manual process with many dangerous application for the welder (pipe hot tapping, underwater welding, etc.). The process robotization seems to be great for safety associated with the improvement of weld quality and repeatability. This work presents a methodology developed for real time trajectory generation for the robotic SMAW. In this methodology, while the electrode is melted the robot makes the diving movement, keeping the electric arc length constant. The trajectory is generated in real-time as a function of melting rate and independent of the welding speed, given by the welding parameters. The proposed methodology uses a variable Tool Center Point (TCP) model where the covered electrode is considered a prismatic joint, whose displacement is determined by the melting rate. The homogeneous transform matrix relating the last manipulator joint and the TCP is then recalculated at each control sampling period. With this methodology, the TCP will always be located at the tip of the electrode (melting front), allowing to program the welding speed independently of the electrode diving speed. This methodology also allows the user to program the weld bead geometry over the joint without caring about the diving movement, which is automatically done by the robot during the welding. This paper also shows some results obtained with the process robotization as welds made on plate and on tubes (linear and circular TCP trajectories).*

Keywords*: Robotic welding, trajectory-generation, SMAW.*

1. INTRODUCTION

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, predominantly manual, since the welder is incapable to weld with repeatability all the weld beads. This process mechanization already exists and increases the repeatability, however it limits the bead geometry, which is determined by the mechanism assembly.

An application to this process is the hot tapping of tubes (Fig. 1). In this application, the welder has to weld a perpendicular tube to a larger one which transports inflammable fluids. As the larger tube cannot be emptied, this is a great dangerous process to a human welder.

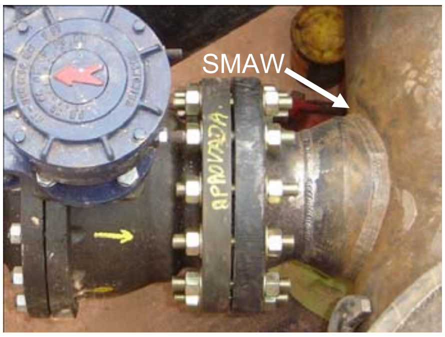

Figure 1. Hot tapping of tubes.

Also, aiming the improvement of the weld quality, allied to the repeatability obtained with 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 coated electrode 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 melted. Thus, if the weld is made using a constant feed speed, it will de obtained a bead with non homogeneous dimensional characteristics (Bracarense, 1994). Its thickness (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 (Batana, 1998) 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.

Industrial robots interfaces usually allow the programming of three types of movements: joint, linear and circular. Joint movements are used for approximation, as it does not guarantee a previously known trajectory to the user. Linear and circular movements are used when it is desired to program a determined trajectory to the robot arm. Due to the 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 start 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 necessary to generate the electrode holder trajectory in real time. This work shows a methodology to the real time trajectory generation to the robotic SMAW. In this methodology, the electrode is considered as an additional (prismatic) joint of the manipulator. This joint's displacement varies in accordance with the electrode melting rate. So, the feeding movement is done in the fusion pool maintaining constant the arc length, independently of the welding speed. To determine the arc length, the weld font voltage and the electrode temperature are monitored, in order to compensate the material electric resistivity increase.

This permits the operator to program the Tool Center Point (TCP) trajectory over the groove to be welded in a transparent way, by simply teaching points in the groove in the same way it would be done in welding processes with automatic wire feed, without needing the knowledge of the melting rate behavior. It is not necessary to program the electrode feed as it is automatically done by the robot controller during the weld by the process monitoring. The shown methodology allows, using the same program, to weld different materials with different electrodes (with different diameters and composition), giving to the SMAW process all the flexibility of other robotic processes. Moreover, this methodology makes possible not only linear grooves welding but also generic geometry groove welding.

1.1. Shielded Metal Arc Welding

The shielded metal arc welding (SMAW) process is, among all other welding processes, one of the simpler ones in terms of equipment, regulation and application (Juers, 1993). It is applied in maintenance, construction and many other activities which need welding. Its main quality is to facilitate the microstructure control and weld bead chemical composition due to the possibility to change the coating composition. The SMAW process offers some advantages compared to other arc welding processes as it is less sensible to air flows and is appropriated to the majority common metals and alloys. Also, it is the most used process in the underwater welding and hot tapping. Figure 2 shows the coated electrode and the electric arc between the electrode and the plate.

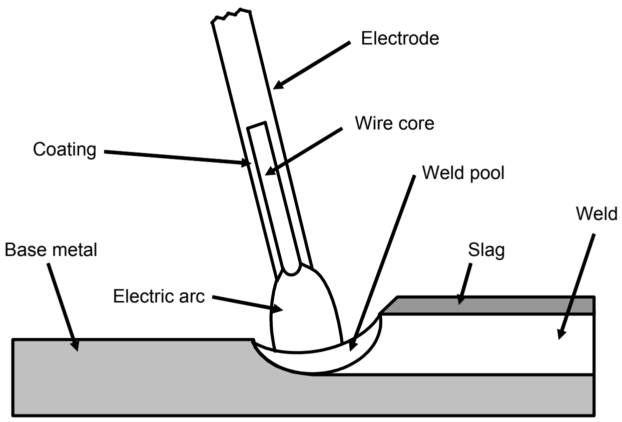

Figure 2. Shielded Metal Arc Welding.

The process starts when the welder touches the base metal with the energized electrode tip, establishing the electric arc. The uncoated electrode face is heated by the arc and burns the coating, inducing some elements ionization which makes stable the electric arc. The welder, then, starts the electrode translation movement over the groove to be welded. As the electrode is melted by the arc temperature and the material is deposited in the groove, the welder has to make also the electrode feeding movement, approaching it to the base metal, in order to make constant the arc length.

A critical point to obtain a good quality weld is the arc length control (Kang, 1996). When the weld is performed in dry ambient, the welder is capable to control the feed speed by the visual observation and the audition of the emitted sound, trying to make constant the arc length. However, in the underwater welding the welder losses its ability to see and hear the electric arc, making the process even more difficult.

In other arc welding processes as the Gas Metal Arc Welding (GMAW) and the Flux Cored Arc Welding (FCAW), the wire is flexible and can be feed by a mechanism as it is melted. So, to program those processes in a robot it is sufficient to program the advance movement over the groove to be welded. However, the coated electrode cannot be reeled, what makes difficult its robotization.

Another limiting factor to the SMAW robotization is the fact that the electric current crosses all the electrode length, causing its heating by Joule effect. This heating, added to the heating caused by the heat conduction over the liquid/solid interface causes an increase in the electrode melting rate, making necessary to increase the electrode feeding speed.

The melting rate is defined as the relation between the consumed length (L) and the time (t):

$$T_f = \frac{dL}{dt}. \tag{1}$$

This rate can be determined by models which relates it with the electrode temperature (Quinn *et al.*, 1997, Batana and Bracarense, 1998) or by indirect arc length measurement using the arc voltage measurement (Kang, 1996).

1.2. Industrial Robots Kinematics Modelling

Attaching one frame to each robotic manipulator joint, one can define for each joint an associated homogeneous transform matrix ${}^{i-1}_{\;\;i}T$ with one degree of freedom, where i-1 is the previous joint in the kinematics chain. The frame {0} is defined as the frame fixed in the robot base and the frame $\{T\}$ is located in the Tool Center Point (TCP).

For a robot with N joints, the transform between the base frame and the $\{N\}$ frame is given by:

$${}^{0}_{N}T = {}^{0}_{1}T \;\; {}^{1}_{2}T \;\; \ldots \;\; {}^{N-1}_{\;\;\;N}T \tag{2}$$

and the transform between the base frame and the tool frame $\{T\}$ is:

$${}^{0}_{T}T = {}^{0}_{1}T \;\; {}^{1}_{2}T \;\; \ldots \;\; {}^{N-1}_{\;\;\;N}T \;\; {}^{N}_{T}T \tag{3}$$

where ${}^{N}_{T}T$ is the transform which describes the tool frame related to the last manipulator joint.

Given the homogeneous transform matrix for each manipulator joint in function of the respective degree of freedom (direct kinematics) it is possible, knowing each joint angle, to calculate the TCP position. The inverse problem solution permits, given the desired position for the TCP, to calculate each joint manipulator position (inverse kinematics).

1.3. Trajectory Generation

Basically, the robot movement programming consists on defining points to be reached by the tool (TCP). From the initial point to the final one on each movement it is necessary to define each joint position at regular time intervals to feed these positions to the joint controller as set-points. This procedure is called trajectory generation.

Based on restrictions as initial and final positions and tool movement speed, the controller plans the trajectory before starting the movement (Fig. 3). After that, at each sampling period, it calculates a new point in the trajectory for the TCP and each joint displacement. These values are sent to each joint controller, which drives the movement.

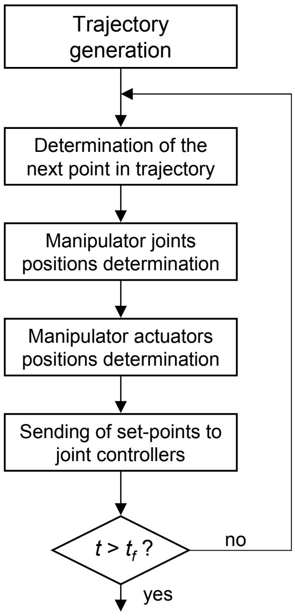

Figure 3. Controller flowchart for robot movement.

2. TRAJECTORY GENERATION FOR SMAW

To make the shielded metal arc welding, it is not sufficient to follow a predetermined trajectory over the groove, as in the GMAW and FCAW processes, in which the wire feeding is automatic. In SMAW, it is necessary to the manipulator to make the feeding movement, in order to maintain constant the electric arc length. As the melting rate is not constant due to the heating caused by the Joule effect, the feeding speed has to be regulated in real-time.

The methodology shown here allows the 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 over the groove without caring about the electrode melting.

The electrode is here considered as a prismatic joint of the manipulator. 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 manipulator kinematics model (Fig. 4). So, the diving movement of the electrode-holder is made independently of the welding movement.

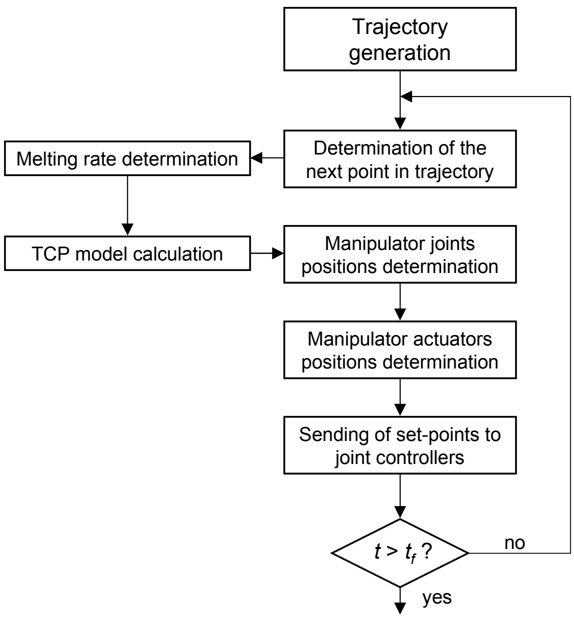

Figure 4. Controller flowchart for shielded metal arc welding.

Figure 5 shows a model for the electrode holder for the robotic SMAW with attached frames.

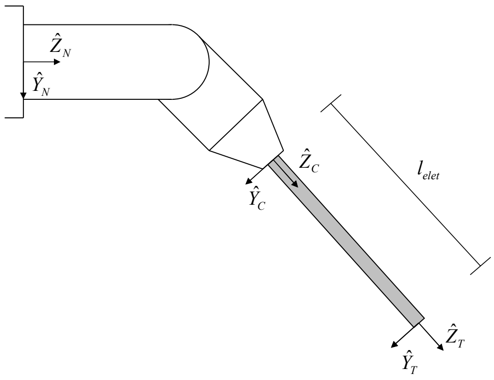

Figure 5. Electrode holder with attached frames.

Considering the frame $\{N\}$ as the last joint frame, $\{C\}$ as an intermediate frame and $\{T\}$ as the TCP frame, it may be determined:

$$
{}^{N}_{T}T = {}^{N}_{C}T\,{}^{C}_{T}T = \begin{bmatrix} & {}^{N}_{C}R & & {}^{N}P_{CORG} \\ & & & \\ & & & \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & l_{elet} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}
$$

where ${}^{N}_{C}R$ and ${}^{N}P_{CORG}$ are constant and depends on the specific electrode holder and ${}^{C}_{T}T$ represents the prismatic joint associated to the electrode.

To calculate the inverse kinematics it is used the relation ${}^{0}_{N}T = {}^{0}_{T}T\,{}^{N}_{T}T^{-1}$ and the manipulator joints positions may be calculated using the inverse kinematics model applied to the matrix ${}^{0}_{N}T$.

Consider, for example, the electrode holder shown in Fig. 6. In Fig. 7 are shown the initial and final manipulator positions considering as the trajectory initial point P_0=[500 0 700]^T and the final point P_f=[750 0 700]^T (a 250mm bead weld).

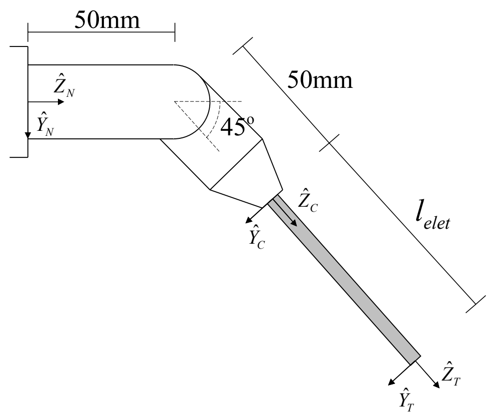

Figure 6. Example of an electrode holder.

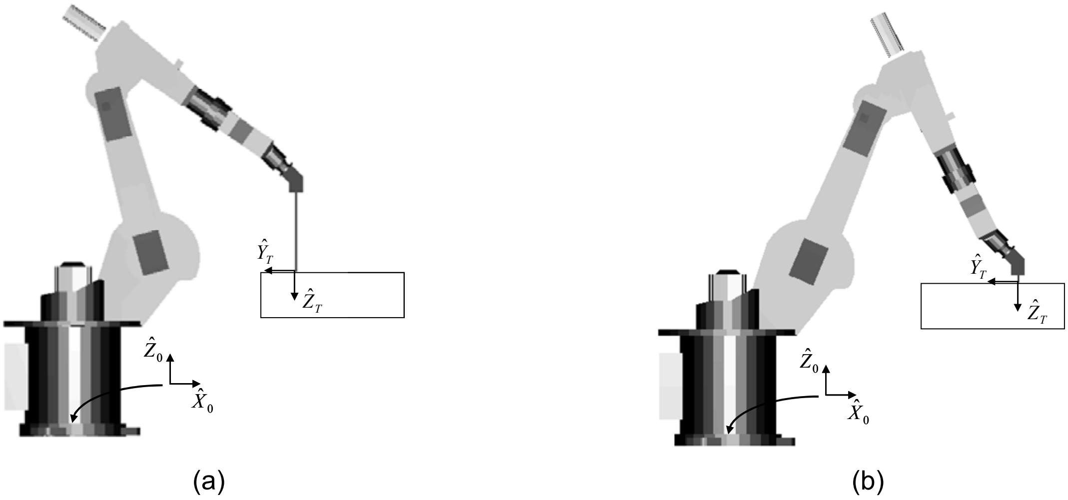

Figure 7. Initial and final manipulator positions.

Considering a welding current of 120A, welding speed of 5mm/s and the melting rate experimentally obtained by (Batana and Bracarense, 1998), Fig. 8 shows the TCP and electrode holder trajectories in the XZ plan. It can be stated that the TCP moves only in the X direction (welding direction), from X=500 to X=750. As the electrode is parallel to the Z axis, the electrode holder diving movement is made in this direction, as it moves in X direction. In this case the independence among the TCP advance movement and the electrode holder diving movement is easily stated.

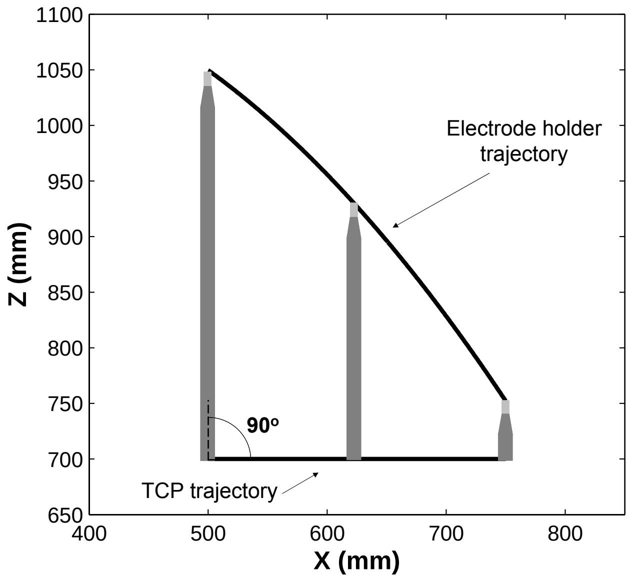

Figure 8. TCP and electrode holder trajectories.

Considering now a welding made using an angle of 45° (Fig. 9), it is possible to state that the diving and advance movements are not independent. Figure 10 shows the TCP and electrode holder trajectories using a 45° angle. For the considered welding conditions, the manipulator advances in direction +X in the beginning of the welding. After approximately 40 seconds, the component of the diving movement in the –X direction becomes higher than the welding speed and the robot has to move the electrode holder in this direction to compensate the increase in the melting rate.

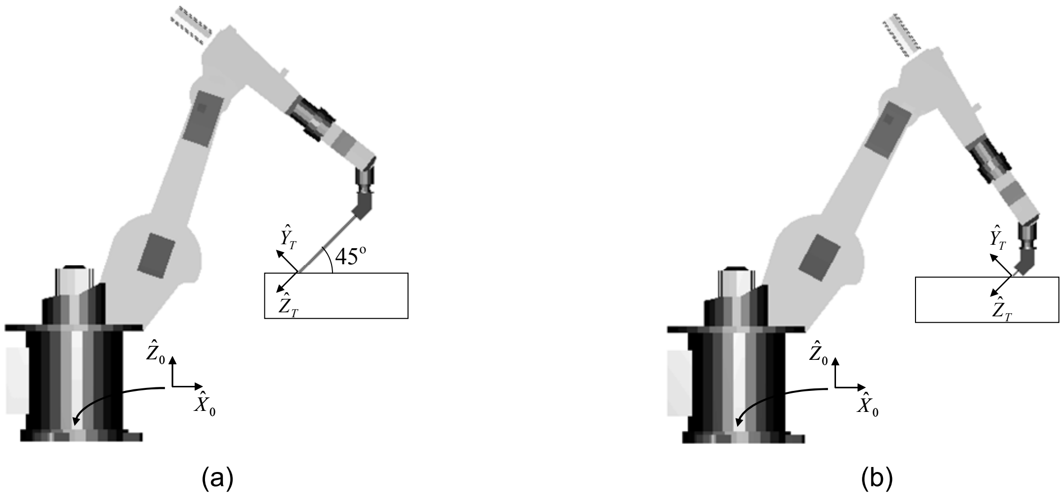

Figure 9. Initial and final manipulator positions for a 45° welding angle.

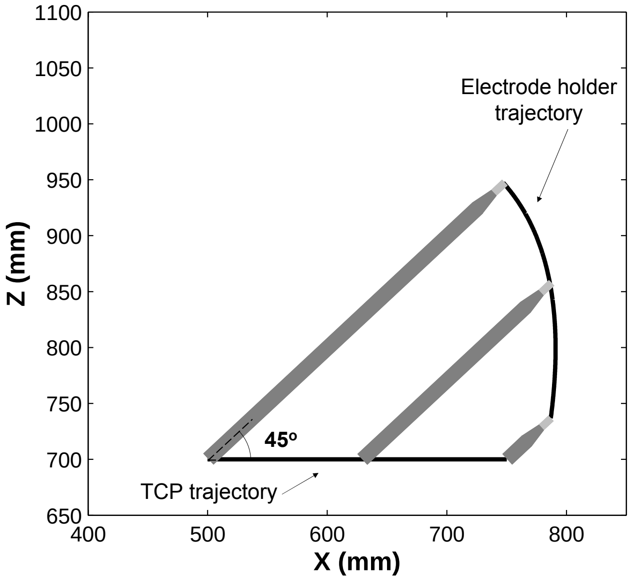

Figure 10. TCP and electrode holder trajectories for a 45° welding angle.

Using this methodology, it is possible to program the welding speed (TCP advance over the groove) independently to the diving speed (variation rate of l_{elet}). Besides this, it is not necessary to the operator know the melting rate behavior, nor how length of the electrode will be melted during the weld. The initial and final points may be programmed using the complete electrode, as the controller will be recording its TCP position ${}^{0}_{T}T(t_0)$. When the program is started the electrode will melt and the new TCP will always be in the melting front.

This methodology can be extended to non linear trajectories, as in the orbital welding or hot tapping of tubes. 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 11 shows the programmed TCP trajectory on the tube and the electrode holder trajectory for 90° of welding angle and Fig. 12 shows those trajectories for 45° of welding angle.

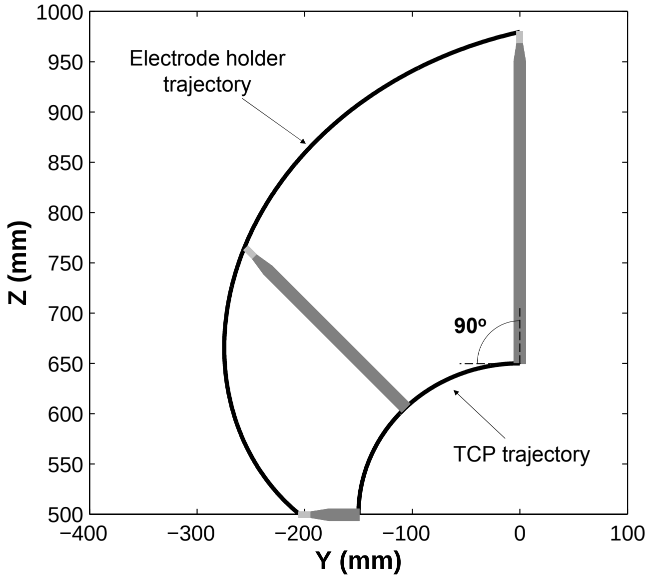

Figure 11. TCP and electrode holder trajectories for a 90° welding angle in orbital welding.

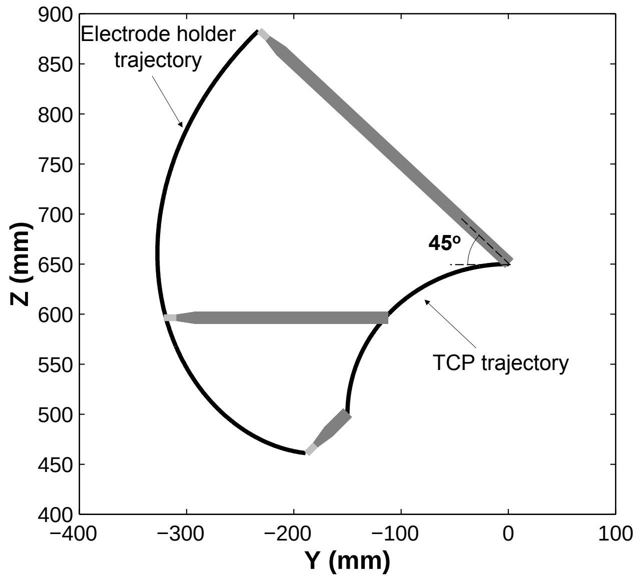

Figure 12. TCP and electrode holder trajectories for a 45° welding angle in orbital welding.

More complex welding trajectories may be programmed by using a sequence of linear and circular movements as in other welding processes.

3. MATERIALS

To validate the shown methodology, it was used an anthropomorphic industrial robot, model KR-16, with 6 degree of freedom. This manipulator uses a KR C2 controller, which programming language (KUKA, 2003) allows from the programming of simple joint to joint, linear and circular movements to the creation of complex programs, including parameters changes in real time. Those characteristics made possible the implementation of the methodology for real time trajectory generation as the arc length control, shown in (Lima II, 2006).

A MasterTIG AC/DC 2500W source was used in the welding tests.

4. RESULTS

Figure 13 shows the robot positioning at the start (opening the electric arc) and end points (closing the electric arc) during the orbital welding. Both points were thought to the robot using the complete electrode.

(a)

(b)

Figure 13. Robot positioning at initial (a) and end points (b) for a orbital welding.

Figure 14(a) shows weld beads done using E7018 electrodes with diameter of 3,25mm. The welding current was 150A and the welding speed 2,5mm. Figure 14(b) shows weld beads over tube using the same electrodes. The welding current was 130A and the welding speed 5,5V.

(a)

(b)

Figure 14. Weld beads over plate (a) and tube (b).

As it can be stated, all the beads have the same aspect, showing the repeatability of the presented methodology.

5. CONCLUSIONS

The presented methodology for the real-time trajectory generation for robotic shielded metal arc welding allows trajectory and welding speed programming independently to the electrode feeding speed. This methodology can be used for any TCP trajectory as the TCP is considered as an additional joint of the manipulator, what permits the TCP, which is always located at the melting front, to follow the programmed trajectory as the electrode is melted. So, the diving movement is done by the robot without needing an independent feeding device.

The methodology flexibility was shown by linear and circular trajectories welding, as any other trajectory can be decomposed as a sequence of such movements.

6. ACKNOWLEDGEMENTS

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