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Model of Root-Bead Welding for Off-line Programming and Control

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Abstract

In this paper, a model is presented which, based on a description of the shape of a welding seam (the gab size and bevel angles), can be used to select variables controlling the welding of a root-bead. The model can be used in an off-line programming system as well as in a geometry-sensor based control system.

The model is a stationary model and it is established on an empirical basis. Tests indicate that the model can be used to select control variables for seams with root gabs between 2 and 5 mm. The allowed deviation from the nominal value of the gab is app. 0.5 mm.

The model has been implemented in an off-line programming system generating robot programs for welding thick walled large diameter nozzles perpendicular onto pipes. Tests with this off-line programming system indicate that if the workpiece geometry is defined sufficient well, a satisfactory weld quality is obtained when executing the control variables computed by the model.

Keywords

Robotics, root-bead welding, off-line programming, process modelling, sensor based control.

1 INTRODUCTION

In many industries, welding fabrication involves many labour intensive manual operations which impose high demands on the skills and concentration of the operator. Because of the significant requirements to the humans involved and the high demands to welding flexibility, automation by robots offers a great potential for many industries to improve welding rates and in particular welding quality.

However, one of the obstacles preventing many industries from using robots to perform welding tasks is the cumbersome work associated with programming the robots. This obstacle is of particular importance when the robots have to be re-programmed often.

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One way to solve this problem is to automate the programming task by using a computer aided off-line programming system. In order to perform computer aided off-line programming of robots for welding tasks (and also other tasks), a number of models are needed: models of the robot and its environment, workpiece models, and inverse welding process models. An inverse welding process model is here defined as: a table or a mathematical equation which transforms the workpiece geometry into appropriate control variables, which, when executed, yield a weld seam fulfilling the required weld quality criterion.

For a large number of welding applications, sufficiently accurate models of the robot and its environment can be designed in off-line programming and simulation systems such as ROBCAD and GRASP. Furthermore, geometrical models of the workpieces to be welded can be designed in CAD-systems.

However, sufficiently reliable inverse welding process models are rarely available. Some models have been developed for the root-beads in seams with backing (Andersen et al (1989), Harrits (1990), Galopin (1991) and Lauridsen (1991)). But for welding root-beads without backing, no inverse welding process model is available.

Because of this, and because such a model is needed in a computer aided off-line programming system used at Odense Steel Shipyard Ltd, Denmark, an inverse welding process model for welding root-beads without backing has been developed at Department of Production, Aalborg University, Denmark. The objective of this paper is to present this model.

2 THE WELDING TASK

The inverse welding process model presented in this paper has been developed so that it can be used at Odense Steel Shipyard, Ltd, Denmark, for welding thick walled large diameter nozzles onto pipes (in the following called pipe branches). Pipe branches of various dimensions are being welded at Odense Steel Shipyard, however, the work presented here is focused on pipe branches having the following characteristics (see figure 1):

- The diameter (D) of the main pipe is larger than the nozzle diameter (d) ($D/d > 1.5$)
- The nozzle centre axis intersects and is perpendicular to the centre axis of the main pipe.
- The diameter of the nozzle is relatively large ($d > 200$mm).
- The nozzle and the main pipe are made of carbon steel (St. 37).

The weld seam is produced by preparing the pipe and the nozzle in a numerically controlled flame-cutting machine. With a vertical cut, a hole is made in the main pipe, and the nozzle is cut such that the resulting weld groove angle (Ω) is app. 45° along the entire seam. Measurements on pipe branches have showed that the variations of Ω usually are less than +/- 2°. The nozzle is tack welded onto the main pipe. It is attempted to have a constant root-gab, but due to various production tolerances (e.g. ovalities of the pipes), the resulting root-gab (d_{root}) varies between 2.0 mm and 5.0 mm. The resulting weld bead must have adequate fusion and convexity of the back face of the weld seam.

The cell in which the robot based nozzle welding is performed consists of a workpiece positioner having one degree-of-freedom, a welding robot and a welding machine. The basic outline of the cell is shown in figure 1. As it appears of this figure, the workpiece is fixed on the workpiece positioner so that the degree of freedom of the positioner (θ) coincides with the centre axis of the main pipe.

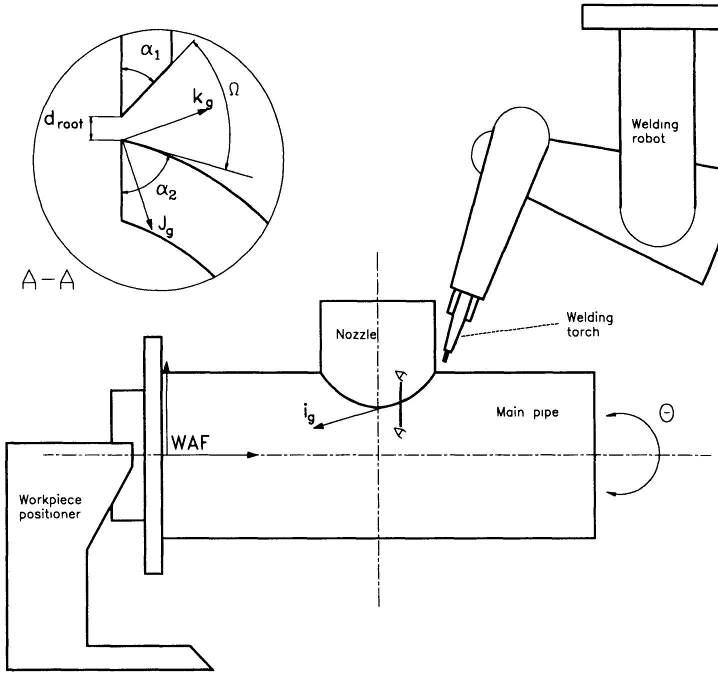

Figure 1 A sketch of the cell performing the welding of the pipe branches

3 MODEL SPECIFICATION.

In this section the input/output to/from the inverse welding process model are defined. However, first it must be stated that the model has been developed for stationary (steady-state) operations. Stationary inverse welding process models can be used to compute trajectories of control variables if the conditions of the weld process is such that it can be assumed that the weld process runs through a number of quasi-stationary states during operation. Experiments indicate that for pipe branches having the characteristics listed in section 2 this is a valid assumption (see Lauridsen et. al. (1995)).

Secondly, it must be stated that the model applies for MAG-welding (gas metal arc welding) only and for the equipment parameters shown in table 1.

Table 1 Equipment parameters used for developing the inverse welding process model

Welding machine:	MIGATRONIC KME400
Wire:	FILARC PZ 6102 (d=1.2mm)
Gas:	$ArCO_2$ 82/18

3.1 Output of the Inverse Welding Process Model.

The output from the inverse welding process model are the values of the variables controlling the weld process in a certain pre-determined point along the welding seam.

There are a large number of variables involved in MAG-welding, and these variables can be defined and selected in various ways depending on the specific welding task. For the welding task presented in this paper, the following variables are used:

- U : The welding voltage.
- W : The wire feed speed.
- θ : The positioner angle (see figure 1).
- v_T : The travel speed (the speed of the torch relatively to the workpiece).
- ${}^{WAF}T_{tnom}$: A transformation matrix specifying the nominal location (position and orientation) of the welding torch relatively to the workpiece attachment frame (WAF). WAF is located on the workpiece attachment plane of the positioner (see figure 1), and the nominal location is defined as the location of the torch if no oscillation is specified.
- OSC : The oscillation pattern specified by (see figure 2):
  - OW : The oscillation width.
  - OV : The oscillation vector represented relatively to WAF.
  - OF : The oscillation frequency.
  - OT : The hold time in percentage of total oscillation time.

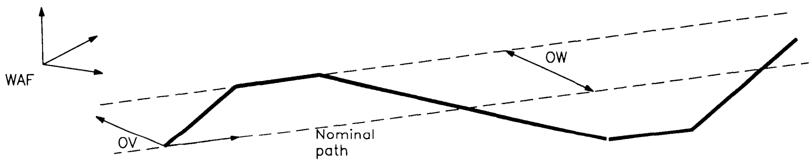

Figure 2 Illustration of the variables specifying the torch oscillation.

How a trajectory of a vector containing the control variables listed above can be transformed into a trajectory of equipment control vectors controlling the equipment shown in figure 1, is described in Madsen&Holm (1994).

3.2 Input to the Inverse Welding Process Model.

The inverse welding process model must be able to compute control variables in all points along the welding seam. For welding of pipe branches, this means that the inverse welding process model must be able to cope with the varying seam profile shapes found when moving along the seam.

As indicated by figure 1, the groove profile can be described by means of the following shape parameters:

α_1 = The bevel angle of the nozzle.
α_2 = The bevel angle of the main pipe.
Ω = The groove angle.
d_{root} = The root gab.

If it is assumed that Ω is constant 45°, and that: $\alpha_1 + \alpha_2 + \Omega = 180°$, then α_1 is dependent of α_2, and the seam profile can be described by two parameters: α_2 and d_{root}. For the pipe branches in this investigation α_2 and d_{root} belongs to the following intervals: $\alpha_2 \in [50° ; 90°]$ and $d_{root} \in [2 \text{ mm} ; 5 \text{ mm}]$

The position and orientation of the groove is represented by a transformation matrix (${}^{WAF}T_{groove}$) which specifies the location of a groove frame relatively to the WAF-frame. In every point along the welding seam, the groove frame is defined as follows (see also figure 1): The origin of the groove frame is located on the edge of the main pipe. The X-axis of the groove frame (represented by the unit vector $\mathbf{i}_g$) is tangent to the spatial curve formed by the groove edge, and the Z-axis (represented by $\mathbf{k}_g$) is parallel with the bisector for the groove. The direction of the Y-axis (represented by $\mathbf{j}_g$) can be found using the right-hand rule.

The orientation of the welding seam relatively to gravity should in principle also be included as input to the inverse welding process model, since gravity has a significant effect on the resulting weld quality. Usually, if the orientation of the welding seam with respect to gravity changes, a change in control variables is needed. However, by using a workpiece positioner as shown in figure 1, it is possible to keep the orientation of the seam with respect to gravity constant along the entire welding seam. How to control the workpiece positioner so that this is obtained is described in Lauridsen et. al. (1994).

4 THE INVERSE WELDING PROCESS MODEL.

In the following, the inverse welding process model will be presented, i.e. it will be described how the transformation shown in figure 3 is carried out.

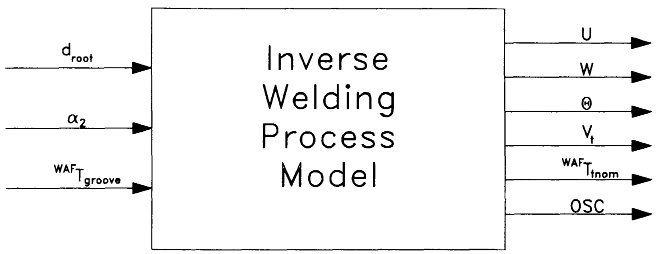

Figure 3 Definition of the task of the inverse welding process model.

Experiments have shown that some of the control variables need not be varied as a function of model input. These constant control variables are shown below in table 2.

Table 2 Constant control variables.

Welding voltage (U):	15.3 V
Wire feed speed (W):	2.5 m/min
Oscillation frequency (OF):	1.8 Hz
Oscillation holding time (OT):	35 %

The transformation from the WAF-frame to the torch frame (${}^{WAF}T_{tnom}$) is computed as:

$$ {}^{WAF}T_{tnom} = {}^{WAF}T_{groove} \cdot {}^{groove}T_{tnom} \tag{1}$$

where ${}^{WAF}T_{groove}$ is known from the model input and ${}^{groove}T_{tnom}$ is a function of the desired tip-to-workpiece distance (D_w), the desired travel angle (α_t), and the desired torch work angle (β_t) (see figure 4 for a definition of α_t and β_t)

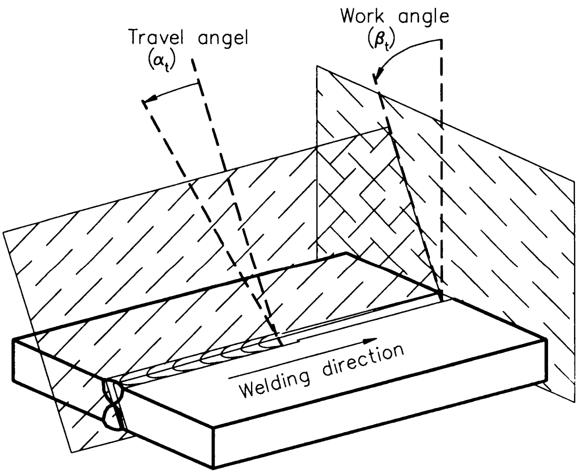

Figure 4 A definition of the angles (α_t and β_t) specifying the torch orientation.

In the model the tip-to-workpiece distance (D_w) is constant = 15 mm, and the travel angle (α_t) is constant = -27°. Experiments have shown that the torch work angle β_t must be varied as a function of α_2 in order to cope with the varying mass distribution along the seam. Experiments have shown that β_t (in degrees) can be computed as:

$$\beta_t = 0.104 \cdot \alpha_2 - 5.351 \tag{2}$$

The oscillation width (OW) is computed as a function of the root-gap:

$$OW = \frac{d_{root}}{2} \tag{3}$$

The oscillation vector (OV) is parallel with the root-gab. This means that OV represented relatively to the groove frame can be computed as:

$$OV = \left(0 \quad -\sin(\alpha_2 + \frac{\Omega}{2}) \quad -\cos(\alpha_2 + \frac{\Omega}{2})\right)^T \tag{4}$$

By means of ${}^{WAF}T_{groove}$ this vector can be transformed into a representation relatively to the WAF frame.

Experiments have shown that the travel speed V_t must be varied as a function of both α_2 and d_{root}. In order to establish this relationship experiments were made in test pieces where α_2 were constant and the root gab varied. Welding was performed with constant travel speed, and the gab sizes at which the welding quality changed from being satisfied to being unsatisfied were determined. By performing this experiment for a number of different travel speeds a tolerance box was determined, inside which the travel speed must be selected. A curve was then drawn inside the tolerance box and, finally, a 3rd order polynomial was fitted to this curve. Such experiments were made for three different α_2-values resulting in the following three 3rd order polynomials:

$$\begin{aligned}
\alpha_2 = 90.0^o: &\quad V_t = 4.828 - 1.550 \cdot d_{root} + 0.160 \cdot d_{root}^2 - 0.002 \cdot d_{root}^3 \\
\alpha_2 = 71.0^o: &\quad V_t = 5.397 - 2.155 \cdot d_{root} + 0.344 \cdot d_{root}^2 - 0.019 \cdot d_{root}^3 \\
\alpha_2 = 51.5^o: &\quad V_t = 4.930 - 1.439 \cdot d_{root} + 0.107 \cdot d_{root}^2 - 0.003 \cdot d_{root}^3
\end{aligned} \tag{5}$$

Given a certain pair of α_2-d_{root}-values, the travel speed is computed as follows: First the root-gab d_{root} is inserted into the three 3rd order polynomials shown above. The result of this are three travel speeds (V_{t90},V_{t71},$V_{t51.5}$) corresponding to the root gab and α_2 = 90°, 71° and 51.5°. A 2nd order polynomial is then fitted to these three travel speeds and their corresponding α_2-values. Finally, the travel speed is computed by inserting the α_2-value into this 2nd order polynomial.

5 MODEL TESTS.

A number of tests have been made in order to test the model. In these experiments linear test pieces with constant α_2 and d_{root} values were produced. The inverse welding process model was then used to compute control variables. These control variables were then executed in a test cell. Figure 5 summarises the results obtained from these tests.

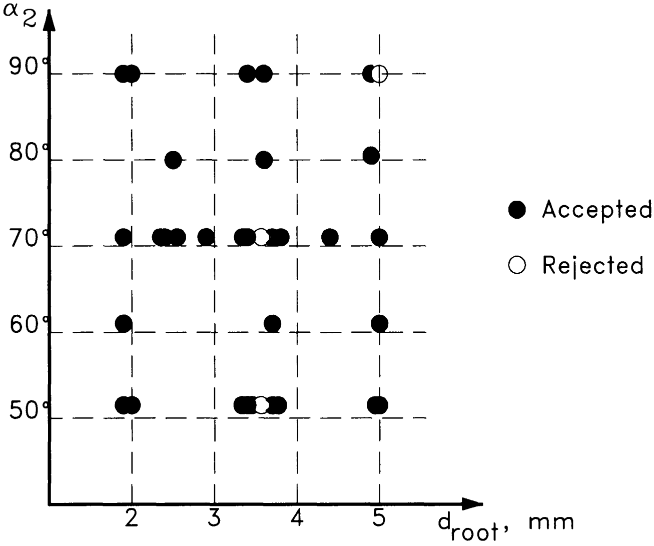

Figure 5 A summary of the experiments made in order to test the inverse welding process model. A total of 37 experiments was carried out.

As it appears from this figure more than 37 test experiments have been performed. Of these 37 experiments only 3 failed to fulfil the quality demands whereas the remaining 34 experiments were accepted. The rejected experiments were repeated, this time resulting in a satisfactory weld quality. Hence, it is evaluated that the rejected experiments failed due to factors outside the scope of the inverse welding process model (e.g. that the thermal distortion of the workpiece was larger than expected).

In order to test the robustness of the model, a number of experiments were made where the inverse welding process model was used to compute control variables for a given model input. These control variables were then executed in seams which had a shape which differed from the shape after which the control variables were computed. The results of these experiments indicated that a satisfactory weld quality can be obtained as long as:

- The misalignment between the two pipe edges is less than ±1 mm.
- The root gap is known with an accuracy of ± 0.5 mm.
- The welding torch is guided in the middle of the weld groove with an accuracy of less than ± 0.3 mm.
- The groove angle (Ω) is $45^o \pm 5^o$.

6 CONCLUSIONS.

In this paper an inverse welding process model has been presented which can compute the variables controlling the welding of a root-bead in a seam with a gab. Input to the model is a description of the shape of the welding seam. Experiments indicate that the model is valid as long as the deviations between the modelled (expected) workpiece shape and the shape of the physical workpiece are below certain thresholds.

The inverse welding process model has been implemented in an off-line programming system for welding pipe branches. Here the model input is computed based on a computer representation of the pipe branch. The off-line programming system is described in Lauridsen et. al. (1995).

The main conclusion from experiments with the off-line programming system is that if the workpiece shape is known sufficiently well, an execution of the control variables computed by the inverse welding process model results in a satisfactory weld result.

However, the experiments also indicated that it is difficult and costly to keep the shape deviation on an acceptable low level. Instead, it is proposed to use a geometry-sensor system to measure the actual seam shape. The architecture of such a system is presented in Madsen&Holm (1995).

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