NONLINEAR INTERVAL MODEL CONTROL OF QUASI-KEYHOLE ARC WELDING PROCESS

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Abstract
This paper addresses the development of a nonlinear model based interval model control system for the quasi-keyhole arc welding process, a novel arc welding process which has advantages over the laser welding process and conventional arc welding processes. The structure of the nonlinear model chosen was proposed based on an analysis of the quasi-keyhole process to be controlled. Because of the variations in the manufacturing conditions, the parameters of the nonlinear model are uncertain but bounded by fixed intervals if the range of the manufacturing conditions is specified. To determine the intervals, extreme operating conditions/parameters (manufacturing conditions) were used to conduct experiments. Each experiment gives a set of model parameters and the interval for each parameter is given by the minimum and maximum among the values obtained from different experiments. Closed-loop control experiments have verified the effectiveness of the developed system as a robust control which requires no re-adjustment and can function properly when fluctuations/variations in manufacturing conditions, and thus the process dynamics, change, vary, or fluctuate.

1. Introduction
Quasi-keyhole arc welding, including controlled keyhole plasma arc welding (PAW) (American Welding Society, 1990) and double-sided arc welding (DSAW) (Zhang and Zhang, 1999; Zhang, Zhang, and Jiang, 2002a), switches the current from the peak to base level after the keyhole is established in order to prevent burn-through, a condition caused by detaching the molten metal in the weld pool from the members of metal to be joined (Liu, 2001; Zhang and Liu, 2002). To establish the keyhole, the peak current must be sufficient. However, if the peak current is too high, the excessive arc pressure may blow liquid metal away, causing burn-through rather than forming a continuous weld (Zhang and Liu, 2002), even before the current is switched to the base level after the keyhole is established. An appropriate peak current is needed to establish the keyhole in an appropriate period.

At the University of Kentucky, a simple, accurate and robust sensor based on the backside efflux plasma charge (Li, Brookfield, and Steen, 1996), which is referred to as EPCS or efflux plasma charge sensor, has been developed to detect the establishment of the keyhole and proven to be valid (Zhang and Zhang, 2001). As can be seen in Fig. 1, if the keyhole has been established, the plasma jet exits from the keyhole and establishes an electrical potential between the work piece and the detection plate. Using the EPCS sensor, a control system has been developed to automatically adjust the peak current for implementing the quasi-keyhole process (Zhang and Liu, 2002). The control algorithm used was the widely used generalized predictive control (Clarke, Mohtadi, and Tuffs, 1987) for linear systems. To overcome the uncertainties in the manufacturing conditions, the parameters of the controlled quasi-keyhole process, defined by its input (amplitude of the peak current) and output (the peak current duration or keyhole establishment period), are identified online. Unfortunately, when the changes or uncertainties of the manufacturing conditions are significant, a certain period is needed before the estimates of model parameters become accurate (Zhang and Liu, 2002). As a result, the weld quality during this period may lack sufficient assurance. Further, if the manufacturing conditions fluctuate, weld quality may not be assured.

It is apparent that manufacturing applications demand a robust control system which can function properly under variations and fluctuations in manufacturing conditions or uncertain process models. In this study, the authors first model the uncertain controlled process as a non-linear interval model whose parameters are not known exactly but are bounded by known intervals and then designed a robust control algorithm for the non-linear interval model. Experiments are then conducted to confirm that the developed control system is capable of producing quality welds when fluctuations/variations in manufacturing conditions occur.

A number of publications have addressed advanced controls of thermal processing (Doumanidis and Fourligkas, 1996a; Doumanidis and Fourligkas, 1996b) and welding (Lankalapalli, Tu, Leong, and Gartner, 1999; Bingul, Cook and Strauss, 2000; Zhao, Chen, Wu, Dai and Chen, 2001; Zhang and Kovacevic, 1998). However, to the best knowledge of the authors, no approaches similar to quasi-keyhole or interval model based control have been
proposed or applied to control uncertain welding processes, except for the previous work done at the University of Kentucky (Zhang and Liu, 2002; Zhang, Liguo, and Walcott, 2002).

2. Process Description

A typical current waveform and efflux signal recorded during quasi-keyhole arc welding process as shown in Fig. 2 can be used to depict the process to be controlled. The corresponding dynamic changes of the weld pool and the keyhole are shown in Fig. 3(b). At instant $t_1$, the current is switched from base to peak current (Fig. 3(a)). The depths of the weld pool and the partial keyhole then increase under the peak current (Fig. 3(b)). At $t_2$, the weld pool becomes fully penetrated and the complete keyhole is established through the thickness of the work-piece (Fig. 3(b)). This instant ($t_2$) can be detected using the efflux signal as the instant when the efflux signal exceeds the preset threshold. In Fig. 2, the current is switched from the peak current to the base current right after the establishment of the keyhole is confirmed. In general, the peak current is switched to the base current $d$ seconds ($d \geq 0$) after the establishment of the keyhole is confirmed. Denote this instant as $t_3$. Then the peak current duration $T_p = t_3 - t_1$. In the case shown in Fig. 2, the delay $d = 0$ and $t_3 = t_2$. Hence, in Fig. 2, $T_p = t_2 - t_1$.

In the proposed quasi-keyhole process, the current is switched back to the peak current $T_p$ seconds after $t_3$ where the base current duration $T_b$ is a pre-programmed fixed parameter. Denote this instant as $t_4$. Assume that the keyhole is confirmed again at $t_4$ and the current is switched to the base current again at $t_5 = t_4 + d$. It is evident that $t_4$ is the $t_1$, $t_5$ is the $t_2$, and $t_6$ is the $t_3$ for the succeeding new pulse cycle. If $t_1$, $t_2$, and $t_3$ are denoted as $t_1(k)$, $t_2(k)$, and $t_3(k)$; $t_4$ and $t_5$ as $T_p(k)$; $t_6$ as $T_b(k)$; the peak current between $t_1$ and $t_3$ as $I_p(k-1)$ (determined in the last cycle before $t_1$); and the base current between $t_3$ and $t_4$ as $I_b(k)$; then $t_4$ can be denoted as $t_4(k+1)$, $t_5$ as $t_5(k+1)$, and $t_6$ as $t_6(k+1)$. Further, $T_p(k+1)$, $T_b(k+1)$, $I_p(k)$, and $I_b(k+1)$ can be defined accordingly. In this way, the process to be controlled in this study is defined as a system whose control variable is $u(k) = I_p(k)$ and whose output is $y(k) = T_p(k)$, as shown in Fig. 4. (For the convenience of further derivation of control algorithm, $u(k)$ and $y(k)$ are denoted as $u_k$ and $y_k$.) The objective of this study is to develop a robust control system in which the control variable is adjusted to achieve the desired output despite the fluctuations/variations in manufacturing conditions.

3. Nonlinear Interval Model

An interval model is a useful description for parametric uncertainty. Much of the success of the parametric approach is restricted to analysis issues (Barmish and Kang, 1993). While the unstructured uncertainty can be well resolved by the $H_\infty$ control, limited progress has been made in achieving an effective systematic design method for the interval plant control (Dehleh, Tesi, and Vicino, 1993). Preliminary results on the regularity of the robust design problem with respect to the controller coefficients were obtained by Vicino and Tesi (1990). Abdallah et al. (1995) and Olbrot and Nikodem (1994) addressed a class of interval plants with one interval parameter. In another study (Zhang and Kovacevic, 1997), a prediction based algorithm with guaranteed robust steady-state performance in tracking a given set-point is proposed to control interval plants described using an (linear) impulse response model.

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If the quasi-keyhole process can be described using a linear model $T_p(k) = \sum_{j=1}^{q} a_j T_p(k-j) + \sum_{j=1}^{p} b_j I_p(k-j)$ where $(p, q)$ is the order of the system and $a_j (j=1,...,p)$ and $b_j (j=1,...,q)$ are the system’s parameters, it may lead to a linear interval model in which the values of the parameters are not known exactly but bounded by fixed intervals $[a_{j_{\min}}, a_{j_{\max}}](j=1,...,p)$ and $[b_{j_{\min}}, b_{j_{\max}}](j=1,...,q)$ such that $a_{j_{\min}} \leq a_j \leq a_{j_{\max}}(j=1,...,p)$ and $b_{j_{\min}} \leq b_j \leq b_{j_{\max}}(j=1,...,q)$. Unfortunately, as discussed below, it is suitable to describe the quasi-keyhole process using a specific non-linear model.

Analysis of the quasi-keyhole process suggests that the peak current duration is directly determined by the amplitude of the peak current because a larger peak current tends to establish the keyhole more quickly or reduce the peak current duration. On the other hand, for the same peak current, if the workpiece has been well heated before
the peak current is applied, the peak current duration or keyhole establishment time can be reduced. Hence, in addition to the amplitude of the peak current, the peak current duration also depends on the temperature in the area where the keyhole is established and the temperature distribution of its surrounding area. However, a direct inclusion of the temperature distribution into the model would require measurement of temperature and complicate the model. As a result, to obtain a simple and effective model, this paper proposes describing the process to be controlled as follows:

\[ T_p(k) = a_0 + a_1 I_p(k-1) + a_2 I_p(k-2)T_p(k-1) + a_3 I_p(k-3)T_p(k-2) + \cdots + a_n I_p(k-n)T_p(k-n+1) \]  

(1)

where \( I_p(k-j-1)T_p(k-j) \) is used to account for the contribution of the heat input in cycle \( k-j \) and \( \sum_{j=1}^{n} a_j I_p(k-j-1)T_p(k-j) \) accounts for a weighted contribution of heat input in previous cycles. (Note: As can be seen in Fig. 3(a), \( T_p(k-j) \) is associated with \( I_p(k-j) \) instead of \( I_p(k-j) \). It is because \( I_p(k-j) \) is determined by the control algorithm after \( T_p(k-j) \) is measured and \( I_p(k-j) \) can only be applied as the peak current to establish the keyhole in the next cycle.) To simplify the notation, \( y \) and \( u \) have been suggested as substitutes for \( pT \) and \( pI \). As a result, equation (1) can be written as

\[ y_k = a_0 + a_1 u_{k-1} + a_2 u_{k-2} y_{k-1} + a_3 u_{k-3} y_{k-2} + \cdots + a_n u_{k-n} y_{k-n+1} \]  

(2)

It is evident that the proposed model is nonlinear because of the cross-product of the input and output. The parameters \( a_j (j = 0, 1, \ldots, n) \) and order \( n \) of the model can be determined from experimental data using the standard least squares method (Ljung, 1997) and F-test. To determine the intervals for the parameters in (2), four sets of (thickness, speed), i.e., (4.7 mm, 2 mm/s), (4.7 mm, 4 mm/s), (6.7 mm, 2 mm/s), and (6.7 mm, 4 mm/s) are selected to represent extreme conditions of interest in this study and used to conduct four extreme condition experiments all using random number between 110 A and 230 A as the peak current (input) sequence. Four sets of data all give \( n = 3 \) but different estimates for \( \theta \), resulting in the following interval model:

\[ 1373.5 < a_0 < 2506.6, \ -2.8 < a_1 < -1, \ -0.7 < a_2 < -0.2, \ -0.3 < a_3 < 0 \]  

(3)

The units of \( y \) and \( u \), millisecond (ms) and ampere (A), define the units of \( a_j (j = 0, 1, \ldots, n) \) in the model; for example, ms is the unit for \( a_0 \), ms/A for \( a_1 \), and 1/A for \( a_2 \) and \( a_3 \).

It can be seen that except for \( a_0 \), all other parameters in the model are negative. This is in accordance with the fact that a large peak current \( u_{k-1} \) and high initial temperature, at which \( u_{k-1} \) starts to apply, reduce the time \( y_k \) necessary to establish the keyhole. Further, \( a_0 \) must be positive so that the peak current duration is not negative. Hence, the resultant model is in accordance with the physics behind the process to be controlled.

4. Control Algorithm

4.1 Control of Linear Interval Model

The control algorithm for the non-linear interval model is a modification of an interval model control algorithm for linear systems (Zhang and Kovacevic, 1997). To describe the non-linear model control algorithm, the original linear model control algorithm must be reviewed. In the original linear model control algorithm, the system is described using an impulse response model:

\[ y_k = \sum_{j=0}^{n} h(j) u_{k-j} \]  

(4)

where \( k \) is the current instant, \( y_k \) is the output at \( k \), \( u_{k-j} \) is the input at \( (k-j) \) \( (j > 0) \), while \( n \) and \( h(j) \)’s are the order and the real parameters of the impulse response function. Assume \( h(j) \)’s \( (1 \leq j \leq n) \) are time-invariant. They are unknown but bounded by the following intervals:

\[ h_{\text{min}}(j) \leq h(j) \leq h_{\text{max}}(j) \quad (j = 1, \ldots, n) \]  

(5)

where \( h_{\text{min}}(j) \leq h_{\text{max}}(j) \) are the minimum and maximum value of \( h(j) \) and known. Assume \( y_0 \) is the given set-point. The objective is to design a controller for determining the feedback control actions \( \{u_k\} \)’s so that the closed-loop system achieves the following robust steady-state performance:

\[ \lim_{k \to \infty} y_k = y_0 \]  

(6)
The upper and lower limits $s_{\text{max}}(i)$ and $s_{\text{min}}(i)$ for the unit step response $s(i)$ can be calculated from (5). To ensure negative feedback control, the following condition is required:

$$s_{\text{max}}(n)s_{\text{min}}(n) > 0 \quad (7)$$

Consider instant $k$ ($k = 1, 2, 3, ...$). Assume the feedback $y_k$ is available and $u_k$ needs to be determined. Model (4) yields

$$\Delta y_k = \sum_{j=1}^{n} h(j) \Delta u_{k-j} \quad (8)$$

where $\Delta u_k = y_k - y_{k-1}$ and $\Delta u_{k-j} = u_{k-j} - u_{k-j-1}$.

Based on Eq. 8, the following equation can be obtained to calculate the output at instant $k+i$ ($i > 0$) when the control actions are kept unchanged after instant $k$:

$$y_{k+i} = y_k + \sum_{j=1}^{i} h(j) \sum_{l=1}^{j} \Delta u_{k-l-j} +\sum_{j=1}^{i} h(j) \Delta u_k \quad (9)$$

For simplification, denote $y_{k+i}|_{\Delta u_{k-j}=0} = y_k (\Delta u_k)$. When $i = n$, Eq. (9) results in

$$y_{k+n} (\Delta u_k) = y_k + \sum_{j=2}^{n} h(j) \sum_{l=1}^{j-1} \Delta u_{k-l-j} +\sum_{j=1}^{n} h(j) \Delta u_k \quad (10)$$

Hence,

$$y_{k+n} (\Delta u_k) = y_k + \sum_{j=2}^{n} h(j) f(j, \Delta U_{k-1}) + s(n)\Delta u_k \quad (11)$$

where, $\Delta U_{k-1}$ represents the knowledge of $(\Delta u_{k-1}, \Delta u_{k-2}, ...)$, and $f(j, \Delta U_{k-1}) = \sum_{l=1}^{j-1} \Delta u_{k-l-j} = u_{k-1} - u_{k-j}$. It is evident that

$$y_{k+n} (\Delta u_{k-1}) = y_k (\Delta u_k)|_{\Delta u_{k-j}=0} = y_k + \sum_{j=2}^{n} h(j) f(j, \Delta U_{k-1}) \quad (12)$$

Thus,

$$y_{k+n} (\Delta u_k) = y_k (\Delta u_{k-1}) + s(n)\Delta u_k \quad (13)$$

The control action $\Delta u_k$ is so determined that:

$$\max y_{k+n} (\Delta u_k) = \max y_{k+n} (\Delta u_{k-1}) + \max (s(n)\Delta u_k) = y_0 \quad (14)$$

It has been proved (Zhang and Kovacevic, 1997) that for the interval plant control problem given by Eqs. 4-6, the control algorithm described in Eq. 14 will yield:

$$\lim_{k \to \infty} y_k = y_0 \quad (15)$$

It is evident that the control algorithm given by Eq. 14 can also be written as:

$$\max (s(n)\Delta u_k) = y_0 - y_k - \sum_{j=2}^{n} \max (h_{\text{min}}(j) f(j, \Delta U_{k-1}), h_{\text{max}}(j) f(j, \Delta U_{k-1})) \quad (14A)$$

Thus, the input of the system can be determined.

### 4.2 Modified Interval Model Control for Nonlinear Model

In order to control the nonlinear interval model of the quasi-keyhole process, certain modifications are needed for the linear model algorithm. For the convenience of control algorithm calculation as will be seen later, it is preferred that a positive change of control action result in a positive steady-state change in the output. Hence, $\theta = -a$ and $\theta_j = -a_j (j = 1, 2, 3)$ are used as the new control variable and new parameters, and the model becomes

$$y_k = a_0 + (-a_1)(-u_{k-1}) + (-a_2)(-u_{k-2}) y_{k-1} + (-a_3)(-u_{k-3}) y_{k-2}$$

$$= a_0 + \bar{a}_1 \bar{u}_{k-1} + \bar{a}_2 \bar{u}_{k-2} y_{k-1} + \bar{a}_3 \bar{u}_{k-3} y_{k-2} \quad (16)$$

As a result,

$$\Delta y_{k+1} = \bar{a}_1 \Delta \bar{u}_{k+1} + \bar{a}_2 [\bar{u}_{k+1} y_k - \bar{u}_{k+2} y_{k-1}] + \bar{a}_3 [\bar{u}_{k+2} \Delta \bar{u}_{k+1} - \bar{u}_{k+3} y_{k-2}]$$

$$= \bar{a}_1 \Delta \bar{u}_{k+1} + \bar{a}_2 \{ y_k \Delta \bar{u}_{k+1} + \bar{u}_{k+2} \Delta y_{k+1} \} + \bar{a}_3 \{ y_{k+1} \Delta \bar{u}_{k+2} + \bar{u}_{k+3} \Delta y_{k+1} \} \quad (17)$$

where $\Delta y_{k+1} = y_{k+1} - y_k$ and $\Delta \bar{u}_{k+1} = \bar{u}_{k+1} - \bar{u}_{k-1}$. Hence,

$$y_{k+1} = y_k + \bar{a}_1 \Delta \bar{u}_{k+1} + \bar{a}_2 [ y_k \Delta \bar{u}_{k+1} + \bar{u}_{k+2} \Delta y_{k+1} ] + \bar{a}_3 \{ y_{k+1} \Delta \bar{u}_{k+2} + \bar{u}_{k+3} \Delta y_{k+1} \} \quad (18)$$
The bounds of \( y_{k+1} \) can thus be calculated:
\[
\begin{align*}
\max y_{k+1} & = y_k + \max \tilde{a}_1 \Delta \tilde{u}_k + \max \tilde{a}_2 \left[ y_k \Delta \tilde{u}_{k-1} + \tilde{u}_{k-2} \Delta y_k \right] + \max \tilde{a}_3 \left[ y_{k-1} \Delta \tilde{u}_{k-2} + \tilde{u}_{k-3} \Delta y_{k-1} \right] \\
\min y_{k+1} & = y_k + \min \tilde{a}_1 \Delta \tilde{u}_k + \min \tilde{a}_2 \left[ y_k \Delta \tilde{u}_{k-1} + \tilde{u}_{k-2} \Delta y_k \right] + \min \tilde{a}_3 \left[ y_{k-1} \Delta \tilde{u}_{k-2} + \tilde{u}_{k-3} \Delta y_{k-1} \right]
\end{align*}
\]
(19)

Using the resultant \( \max y_{k+1} \) and \( \min y_{k+1} \), the bounds of \( y_{k+2} \) under the assumption of \( \tilde{u}_{k+1} = \tilde{u}_k \) can then be calculated:
\[
\begin{align*}
\max y_{k+2} & = \max y_{k+1} + \max \tilde{a}_1 \Delta \tilde{u}_k + \max \tilde{a}_2 \left[ y_{k+1} \Delta \tilde{u}_{k-1} + \tilde{u}_{k-2} \Delta y_{k+1} \right] \nonumber + \max \tilde{a}_3 \left[ y_{k+1} \Delta \tilde{u}_{k-2} + \tilde{u}_{k-3} \Delta y_{k+1} \right] \\
\min y_{k+2} & = \min y_{k+1} + \min \tilde{a}_1 \Delta \tilde{u}_k + \min \tilde{a}_2 \left[ y_{k+1} \Delta \tilde{u}_{k-1} + \tilde{u}_{k-2} \Delta y_{k+1} \right] \nonumber + \min \tilde{a}_3 \left[ y_{k+1} \Delta \tilde{u}_{k-2} + \tilde{u}_{k-3} \Delta y_{k+1} \right]
\end{align*}
\]
(20)

Similarly, the bounds of future outputs under \( \tilde{u}_{k+j} = \tilde{u}_k \) for \( j > 0 \) can be recursively calculated up to instant \( k+m \) until the output settles at its steady-state value:
\[
\begin{align*}
\max y_{k+m} & = \max y_{k+m-1} + \max \tilde{a}_1 \Delta \tilde{u}_{k+m-1} + \max \tilde{a}_2 \left[ y_{k+m-1} \Delta \tilde{u}_{k+m-2} + \tilde{u}_{k+m-3} \Delta y_{k+m-1} \right] \nonumber + \max \tilde{a}_3 \left[ y_{k+m-1} \Delta \tilde{u}_{k+m-2} + \tilde{u}_{k+m-3} \Delta y_{k+m-1} \right] \\
\min y_{k+m} & = \min y_{k+m-1} + \min \tilde{a}_1 \Delta \tilde{u}_{k+m-1} + \min \tilde{a}_2 \left[ y_{k+m-1} \Delta \tilde{u}_{k+m-2} + \tilde{u}_{k+m-3} \Delta y_{k+m-1} \right] \nonumber + \min \tilde{a}_3 \left[ y_{k+m-1} \Delta \tilde{u}_{k+m-2} + \tilde{u}_{k+m-3} \Delta y_{k+m-1} \right]
\end{align*}
\]
(21)

It is found that \( m = 3 \) is sufficient for the quasi-keyhole process addressed in this study.

The linear model control algorithm determines \( \tilde{u}_k \) such that the maximum of the steady-state output equals the set-point when \( \tilde{u}_{k+j} = \tilde{u}_k \) for \( j > 0 \), and an analytical solution can be obtained for \( \tilde{u}_k \). For the non-linear model control algorithm, the control criterion is also
\[
\max y_{k+m} \big|_{\tilde{u}_{j+k}, A \tilde{u}_{j+k} < 0} = y_0
\]
(23)

However, the solution for \( A \tilde{u}_k \) is not analytical. Since \( \max y_{k+m} \big|_{\tilde{u}_{j+k}, A \tilde{u}_{j+k} < 0} \) only varies with \( A \tilde{u}_k \) for the given previous set of system output and input \( (y_k, y_k, \ldots; y_{k-1}, \tilde{u}_{k-1}, \tilde{u}_{k-2}, \ldots) \), \( A \tilde{u}_k \) can be effectively determined without extensive computation. In this study, \( \max y_{k+m} \big|_{\tilde{u}_{j+k}, A \tilde{u}_{j+k} < 0} \) is calculated first. If \( \max y_{k+m} \big|_{\tilde{u}_{j+k}, A \tilde{u}_{j+k} < 0} \) is smaller (larger) than \( y_0 \), \( A \tilde{u}_k \) will be positive (negative). Then the magnitude of \( A \tilde{u}_k \) can be increased gradually so that (23) is satisfied in a given accuracy. After \( A \tilde{u}_k \) is determined, the control action \( u_k = -\tilde{u}_k = - (\tilde{u}_{k-1} + A \tilde{u}_k) \) can be calculated.

It should be noted that the original algorithm for the linear interval model requires to predict the maximal output after the system reaches the steady-state in order to assure the stability and performance for the resultant closed-loop system. In the modified algorithm for the non-linear interval model, the prediction is made for the maximal output with \( m = 3 \) before the steady-state is completely reached in order to reduce the computation. The stability and performance are thus not guaranteed. For this study, it is found that \( m = 3 \) (i.e., predicting the maximal output 3-steps-ahead) be sufficient for the quasi-keyhole process addressed; however, for other applications, the prediction may have to be made more steps ahead in order to achieve satisfactory results.

5. Experiments

To test the robustness of the developed system, bead-on-plate welding experiments were conducted with the experimental setup shown in Fig. 1.

5.1 Linear Model Based Control

To justify the necessity for the use of a nonlinear model, four linear impulse response models have been obtained using the least square method and F-test from the four sets of experimental data. As a result, an envelope defined by \( h_{\text{min}}(j) \sim j (j = 1, 2, \ldots, n) \) and \( h_{\text{max}}(j) \sim j (j = 1, 2, \ldots, n) \) can be obtained together with the order \( n \) which was found to be 13. Using the linear control algorithm proposed in (Zhang and Kovacevic, 1997) and restated in Eqs. 4-6, and 14, a linear interval model based control algorithm has been designed and experimentally tested on 6.7mm thick stainless steel (304). The travel speed used was 2.3 mm/s and the set-point was 500ms. The control signal and closed-loop system output are given in Fig. 5. It can be seen that both the control variable and output fluctuate.
after a few adjustment cycles. As can be seen from the back-side of the work-piece given in Fig. 9(c), despite the peak current was increased to supply more energy on the plate. As a result, the output returned to the desired level after the initial period of identification, the fluctuation of the output and control variable is acceptable despite the application of the artificial disturbance of travel speed.

As can be seen in Figs. 5 and Fig. 6, the performance of the linear model based predictive control. However, the initial identification and control penalty used in the latter are in general undesirable. A global nonlinear model appears necessary in order to work under possible fluctuations/variations/changes in manufacturing conditions.

5.2 Thickness Experiments

Although the thickness may not change during welding, it does vary from application to application. The objective of this study is to develop a robust control system which requires no readjustment for the parameters of the controller so that it can be directly applied to various applications of interest. Hence, to test the effectiveness of the designed control system, it is necessary to conduct experiments on different thicknesses. In this study, the range of thickness of interest is from 4.7 mm to 6.7 mm. Hence, in this group of experiments, two extreme thicknesses, 4.7 mm and 6.7 mm, were used to simulate two different applications. The parameters of the nonlinear model based interval control algorithm were exactly the same for two experiments.

The peak currents were 198 A and 171 A during the first 3 weld cycles for the 6.7 mm and 4.7 mm thick work pieces, respectively. (If a 171 A were used as the initial peak current for the 6.7 mm thick work piece, the time needed to establish the keyhole would be too long so that the closed-loop control algorithm would not start to function.) The set-point, welding speed, and material were 300 ms, 2 mm/s and stainless steel (304), respectively for both experiments. Figs. 7 and 8 show the outputs, control signals, and back-side welds for the two experiments.

The results in Figs. 7 and 8 can further elaborated below. First, as can be seen in Figs. 7(a)(b) and Figs. 8(a)(b), at the beginning of the weld, because the workpiece is cool, much more energy is needed to heat and penetrate it. Hence, the output, i.e., the time needed to establish the keyhole, in the first few weld cycles is much larger than in those that followed. Second, a 6.7mm thick work piece needs much more energy to be penetrated than a 4.7mm thick one. Hence, although the initial peak current during this initial period is larger, the output associated with the 6.7 mm thick work piece is thus much larger than that associated with the 4.7 mm thick work piece. Third, in both experiments, after 6-7 weld cycles, the heat distribution almost settled and the process became stable. The peak currents only varied within small ranges and the peak current duration in both experiments converged to the desired value of 300ms. Fourth, for the 4.7mm thick work piece, the initial peak current (171 A) was greater than the value needed to establish the keyhole in the desired 300 ms. Hence, the controller automatically decreased the current (Fig.7). However, for the 6.7mm work piece, a peak current larger than the initial value of 198 A was needed to establish the keyhole in 300 ms. As a result, the peak current increased to the appropriate level for establishing the keyhole in 300 ms. Fifth, after the initial steps, the peak current fluctuated. However, the period of fluctuation was brief and the magnitude of fluctuation and its effect on the process are acceptable. Sixth, the results of the closed-loop control in these two extreme experiments of thickness are satisfactory and much better, in terms of fluctuations of control actions and outputs and of response speed, than those obtained using adaptive predictive control which can be considered a local linearization based control.

5.3 Speed Variation Experiments

To test the effectiveness of the designed control system in overcoming extreme disturbances/fluctuations/variations/changes in manufacturing conditions, the welding speed in this speed variation experiment has been changed from 2 mm/s to 4 mm/s at the 25th weld cycle. The experiment was conducted on 4.7mm thick stainless steel (type 304). Except for the welding speed, other welding parameters were kept the same as in the other experiments. Fig. 9 shows the peak current and peak current duration. As can be seen in the figure, the peak current duration did increase after the speed increase. However, because of the closed-loop control, the peak current was increased to supply more energy on the plate. As result, the output returned to the desired level after a few adjustment cycles. As can be seen from the back-side of the work-piece given in Fig. 9(c), despite the
change in the back-side width at the point of 4 cm, the width is stabilized and maintained invariantly after a few millimeters of welds.

6. Conclusion

Based on the non-linear models obtained from the four extreme condition experiments, a nonlinear model based interval model control system is designed. Experiments suggested that the nonlinear model based interval model control has advantages over the linear model based interval model control and the linear model based adaptive predictive control in terms of fluctuations of the control signal and output and of the system response speed. Experiments have also verified the effectiveness of the developed system as a robust control which requires no re-adjustment and can function properly when fluctuations/variations in manufacturing conditions, and thus the process dynamics, change, vary, or fluctuate.

This study used four extreme experiment conditions to obtain the parameter intervals. If the welding speed or the thickness are beyond the ranges of interest, i.e., 2 mm/s to 4 mm/s and 4.7 mm to 6.7 mm, or other welding parameters such as the material and shield gas are different from those used in this study, the effectiveness of the developed control system may not been assured. To develop an effective robust control system, the extreme points must be designed based on careful analysis of the effects of the manufacturing conditions and their ranges such that the intervals are adequate but not too excessive resulting in an over conservative control.

The previous paper (Zhang and Liu, 2002) modeled the quasi-keyhole process as a linear system and used an adaptive predictive algorithm to control it. However, it required an initial period to revise the model from its nominal version, which may not be accurate for the current state of the manufacturing conditions. Further, to reduce the fluctuation in the control action, a penalty was included for the change of the control in the cost function. In this study, the process is described more reasonably using a nonlinear interval model which was derived from an analysis of the process. The non-linear interval model control algorithm requires no real-time parameter identification and artificial penalty on the change of the control. The issue of possible divergence associated with the adaptive algorithm is also eliminated. The resultant system can thus better suit applications in the manufacturing environment.

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Fig. 1 Integrated Sensor and Fixture.

Fig. 2 Typical Current Waveform and Efflux Signal during Quasi-keyhole Arc Welding.

Fig. 3 (a) Time sequence

Fig. 3 (b) Keyhole and weld pool development

Fig. 3 Dynamic Development in Quasi-keyhole Process.
Fig. 4 Proposed Control System.

Fig. 5 (a) Output
Fig. 5(b) Control action
Fig. 5 Experimental Result of Linear Model Based Interval Model Control.

Fig. 6(a) Output
Fig. 6(b) Control action
Fig. 6 Linear Model Based Adaptive Control Experiment under Varying Travel Speed.

Fig. 7 (a) Output
Fig. 7(b) Control action
Fig. 7(c) Back-side weld
Fig. 7 Non-linear Model Based Interval Model Control Experiment on 6.7 mm Thick Plate. Closed-loop control begins at cycle 4.

Fig. 8(a) Output                              Fig. 8(b) Control action
Fig. 8(c) Back-side weld
Fig. 8 Non-linear Model Based Interval Model Control Experiment on 4.7 mm Thick Plate. Closed-loop control begins at cycle 4.

Fig. 9(a) Output                              Fig. 9(b) Control action
Fig. 9(c) Back-side weld
Fig. 9 Non-linear Model Based Interval Model Control Experiment under Speed Variation. The speed is changed at cycle 25.