Modeling and control of quasi-keyhole arc welding process

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Abstract

Quasi-keyhole is a novel approach proposed to operate the keyhole arc welding process. Because the method’s effectiveness depends on the amperage of the peak current used to establish the keyhole, this paper proposes adjusting the amperage based on the duration of the peak current, which equals the keyhole establishment time. A nominal model structure has been selected from those identified using experimental data and been used in the design of an adaptive predictive control system. Closed-loop control experiments have been conducted to verify the effectiveness of the developed system under varying set-points and varying travel speeds.

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1. Introduction

Keyhole arc welding (KAW), including keyhole plasma arc welding (PAW) (American Welding Society, 1990) and the patented keyhole double-sided arc welding being developed at the University of Kentucky (Zhang & Zhang, 1999), has significant advantages over laser welding in industrial applications in terms of cost, application range, safety, joint preparation, etc. It uses a special torch (referred to as a plasma arc torch by the welding community) with a constraining orifice (Fig. 1) so that the electrons emitted from the tungsten electrode flow through the ionized plasma gas and form a highly constrained plasma jet. This highly constrained plasma jet can displace the molten metal in the weld pool to form a cavity (referred to as the keyhole) through the thickness of the work-piece. As a result, the plasma jet can heat the work-piece through the thickness in a manner similar to that of laser welding. However, in comparison with laser welding, KAW still has a larger weld pool (molten metal area). If a control technology can be developed to minimize the heat input and the weld pool, KAW will become a promising process for applications which otherwise require laser welding.

In normal welding practice using KAW, the keyhole is maintained open. To this end, the welding current must be sufficiently high. However, because the arc pressure is proportional to the square of the current (Rokhlin & Guu, 1993), the high current tends to blow the melted metal away from the weld pool, causing burn-through or cutting instead of joining. The authors thus propose switching the current from the peak level to a lower base current level as soon as the establishment of the keyhole is detected. In this way, while the establishment of the keyhole ensures the desired full penetration, the base current allows the melted metal to solidify and the keyhole to close so that burn-through is prevented. After a specified period of base current, the peak current is applied again to re-establish the keyhole, beginning a new pulse cycle. As a result, the process is not maintained in the keyhole mode as it is classically defined, but in a repeated establishing-closing-solidifying mode which is termed quasi-keyhole by the authors.

Because the current is automatically switched to the base level to close the keyhole and solidify the melted metal once establishment of the keyhole is confirmed, the quasi-keyhole approach possesses thereby an inherent mechanism to quickly adapt to varied or varying manufacturing conditions. However, to assure the
effectiveness of the quasi-keyhole approach, the amperage of the peak current must be appropriate: i.e., large enough to establish the keyhole in a specified period of time which can assure the melted metal in adjacent cycles to overlap and thus form a continuous weld, but not excessive such that the melted metal is detached from the weld pool to cause burn-through even before the process responds to the sensor signal. Hence, the selection of the peak current is critical in successfully implementing the quasi-keyhole process.

This paper takes a feedback control approach to resolve the peak current selection issue. To this end, the authors propose adjusting the amperage of the peak current such that the keyhole is established in a desired period of time, which can be directly determined based on weld pool size and travel speed to assure the formation of continuous weld. As a result, a double-loop system shown in Fig. 2(a) is proposed to achieve a controlled quasi-keyhole process by using an automatically adjusted peak current. This system uses a pulsation controller in its inner-loop to switch from the peak current to the base current after the keyhole is detected and then switch the current from the base level to the peak level once the base current has been applied for a pre-specified period. In its outer loop, the amperage controller adjusts the amperage of the peak current \( I_p \) to maintain the peak current duration \( T_p \) at the desired value which has been pre-specified. Hence, the feedback control problem is to design the amperage controller for the quasi-keyhole process to be controlled such that its input (amperage of the peak current) is adjusted to achieve the desired output (peak current duration). The resultant feedback control system is shown in Fig. 2(b).

A number of publications have addressed advanced controls of thermal processing (Doumanidis & Fourligkas, 1996a, b) and welding (Lankalapalli, Tu, Leong, & Gartner, 1999; Bingul, Cook, & Strauss, 2000; Zhao, Chen, Wu, Dai, & Chen, 2001; Zhang & Kovacevic, 1998). However, to the best knowledge of the authors, no approaches similar to quasi-keyhole have been proposed. The derivation and solution of the control problem documented in this paper will establish the foundation for the quasi-keyhole based control of welding process.

2. Experimental system

The hardware system by which the quasi-keyhole process is implemented and controlled is shown in Fig. 3. It includes a welding power supply which receives commands from an analog interface to adjust its output current, a one-dimensional motion system which receives commands from an analog interface to adjust the travel speed, a fixture which holds the work-piece, and a keyhole sensor which provides information on the state of the keyhole.

The University of Kentucky has been working on developing practical keyhole sensors for different applications (Zhang, Zhang, & Liu, 2001; Zhang & Zhang, 2001). The keyhole sensor used in this paper is based on an integrated design of the probe and fixture as
3. Controlled process

A typical current waveform and efflux signal recorded during quasi-keyhole arc welding process as shown in Fig. 5 can be used to better depict the process to be controlled. The corresponding dynamic changes of the weld pool and the keyhole are shown in Fig. 6(b). At instant \( t_1 \), the current is switched from base to peak current (Fig. 6(a)). The depths of the weld pool and the partial keyhole then increase under the peak current (Fig. 6(b)). At \( t_2 \), the weld pool becomes fully penetrated and the complete keyhole is established through the thickness of the work-piece (Fig. 6(b)). This instant \( t_2 \) can be detected using the efflux signal as the instant when the efflux signal exceeds the pre-set threshold. In Fig. 5, 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 \( (d > 0) \) 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. 5, the delay \( d = 0 \) and \( t_3 = t_2 \). Hence, in Fig. 5, \( T_p = t_2 - t_1 \).

In the proposed quasi-keyhole process, the current is switched back to the peak current \( T_b \) seconds after \( t_3 \) where the base current duration \( T_b \) is a pre-programmed fixed parameter. Denote this instant as \( t_6 \). Assume that the keyhole is confirmed again at \( t_5 \) and the current is switched to the base current again at \( t_6 = t_5 + d \). 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 \( t_3(k) \), \( t_5 - t_1 \) as \( T_p(k) \), \( t_4 - t_3 \) as \( T_b(k) \), the peak current between \( t_1 \) and \( t_3 \) as \( I_p(k) \), and the base current between \( t_3 \) and \( t_4 \) as \( I_b(k) \), then \( t_6 \) can be denoted as \( t_4(k + 1) \), \( t_5 \) as \( t_2(k + 1) \), and \( t_6 \) as \( t_3(k + 1) \).

Further, \( T_p(k + 1) \), \( T_b(k + 1) \), \( I_p(k + 1) \) and \( I_b(k + 1) \) can be defined accordingly. In this way, the control variable \( I_p(k) \) and output \( T_p(k) \) sequences which will be used in modeling and control are defined. The dynamic model to be identified is thus a mathematical relation shown in Fig. 4. This keyhole sensor is referred to as the efflux plasma charge sensor (EPCS) (Zhang & Zhang, 2001). As can be seen in Fig. 4, after the keyhole is established, the plasma jet must exit through the keyhole. The efflux plasma will establish an electrical potential between the work-piece and the detection plate, which is electrically isolated from the work-piece, due to the phenomenon of plasma space charge (Li, Brookfield, & Steen, 1996). However, if the keyhole is not established, there will be no efflux plasma between the work-piece and the detection and thus no electrical potential established. Hence, it is possible to measure the electrical potential, or the voltage across the resistor, to determine the intensity of the efflux plasma and thus the establishment of the keyhole.
between the control variable sequence \( \{I_p(k)\} \) and the output sequence \( \{T_p(k)\} \).

4. Modeling of controlled process

4.1. Model structure

Theoretically, a set of governing equations can be written for any welding process and can be numerically solved to analyze the dynamic behaviors of the welding process to be controlled. Unfortunately, limited work has been published for keyhole arc welding processes. Toward a better understanding of quasi-keyhole arc welding as a process to be controlled, a numerical model has been recently developed to analyze the dynamic process of keyhole establishment during double-sided arc welding (Sun, Wu, Dong, & Zhang, 2003). To describe the dynamic behavior of the quasi-keyhole process, the analysis should be conducted over a number of pulsation cycles. Because the completion of such an analysis needs significant effort over a long period and the resultant model will be likely to be nonlinear and manufacturing condition dependent, the authors decided to obtain an empirical model under the guidance of system identification theory (Ljung, 1997) and then verify the effectiveness of the empirical model and the designed control system via experiments.

A preliminary analysis of the thermal process during arc welding suggests that the peak currents in the previous cycles affect the initial temperature of the present cycle and should be included to predict the peak current period. Also, the peak current periods in the previous cycles should be included for auto-regression which is needed in modeling a dynamic system. For simplification, the following linear discrete-time model is proposed for the quasi-keyhole process to be controlled:

\[
y(k) = a_1 y(k-1) + \cdots + a_n y(k-n) = b_1 u(k-1) + \cdots + b_m u(k-m) + \eta(k),
\]

where \( y(k) = T_p(k), u(k) = I_p(k), \) and \( \eta(k) \) are the output (peak current duration), the control variable (amperage of the peak current), and the disturbance at instant \( k \) respectively; \( a_i (i = 1, \ldots, n) \) and \( b_j (j = 1, \ldots, m) \) are the model parameters; \( n \) and \( m \) are the orders of the polynomials \( A(q^{-1}) = 1 - a_1 q^{-1} - \cdots - a_n q^{-n} \) and \( B(q^{-1}) = b_1 q^{-1} + \cdots + b_m q^{-m} \) where \( q^{-1} \) is the delay operator. Further, the disturbance is considered a sum of a constant disturbance \( c_0 \), a moving average of the base current in previous periods \( \sum_{l=1}^{n} c_l I_b(k-l) \), and a
The second step is to design experiments to generate experimental data for model identification. The complete procedure for the determination of the base current, the period of the base current, the permitted range of the peak current, the travel speed, the flow rates of the shielding gas and plasma gas as documented in Liu (2001) suggests that the ranges from 115 to 130 A and from 15 to 30 A are appropriate for the peak current and base current, respectively. White noises with even distribution in (115 A, 130 A) and in (15 A, 30 A) have been generated as \( \{u(k)\} \) and \( \{I_b(k)\} \) respectively for the identification experiments. Figs. 7(a) and 8(a) illustrate two input \( \{I_b(k), u(k)\} \) sequences designed. Using these two input sequences, two quasi-keyhole welding experiments have been performed. Figs. 7(b) and 8(b) plot the experiment output \( \{y(k)\} \) sequences.

In the third step, the experimental data is used to fit the model parameters and determine the order using the least-squares algorithm (Ljung, 1997) and F-test (\( \alpha = 0.05 \)). The detailed step-by-step identification procedure documented in Liu (2001) resulted in two different structures, \( (n,m,o) = (5,3,1) \) (model 1) and \( (n,m,o) = (2,2,1) \) (model 2), for experiments 1 and 2, respectively. Fig. 9 shows the fitting accuracy by comparing the

\[
\eta(k) = c_0 + \sum_{i=1}^{a} c_i I_b(k-l) + e(k). \tag{2}
\]

In general, \( e(k) \) may be stationary but not necessarily white. For simplification, this paper assumes the stochastic process be a Gaussian white noise \( e(k) \sim N(0, \sigma^2) \), i.e., \( e(k) = \varepsilon(k) \). As a result, the dynamic model of the controlled process can be expressed as

\[
y(k) = c_0 + a_1 y(k-1) + \cdots + a_n y(k-n) \\
+ b_1 u(k-1) + \cdots + b_m u(k-m) \\
+ c_1 I_b(k-1) + \cdots + c_o I_b(k-o) + \varepsilon(k). \tag{3}
\]

4.2. Model identification

It would be ideal if both the structure and parameters of the model could be derived from first principles using parameterized operational conditions. To use such a model for welding process control, the operational conditions or manufacturing conditions need to be monitored. The resultant system would require multiple sensors and thus would become unsuitable for manufacturing applications. Hence, although a mathematical formulation of dependence of model parameters on the manufacturing conditions based on first principles would be ideal, the complexity of monitoring manufacturing conditions reduces its effectiveness in manufacturing applications. As a result, a system identification approach together with knowledge of the process is used to obtain an empirical model.

The first step in identifying the model is to ask whether the proposed model structure is capable of describing the dynamics of the process to be controlled. Based on knowledge of the process, the answer is yes. The quasi-keyhole process to be controlled is not a sampled system, but a natural discrete-time system. This implies that any first principle derived model would also have a structure similar to that given in Eq. (1), although the model parameters would be expressed as functions of parameterized manufacturing conditions. Also, the period \( y(k) = T_p(k) \) needed to establish the keyhole in the present cycle is determined primarily by the manufacturing conditions and the initial temperature distribution; the previous peak current periods \( y(k-j)'s \) can indicate the manufacturing conditions, and the initial temperature distribution in the present cycle primarily depends on \( u(k-j)'s \) (the peak currents in the previous cycles) when the travel speed is given. Hence, the model structure proposed in Eq. (1), which uses the previous peak current periods and peak currents as regression factors, is capable of describing the dynamics of the quasi-keyhole process to be controlled.

\[ T_p(k) = \text{function of } y(k-j)'s, u(k-j)'s \]

\[ y(k) = \text{function of } T_p(k) \]
model calculated output with the measured output which has been used to fit the model. In Fig. 10, the measured output in a data set is predicted using the model fitted from another data set. It is found that the predicted output, using the model obtained either from the same data set or another data set, is in reasonable agreement with the measured output. This suggests that the identified models can be considered reasonable from a data analysis point of view.

In the final step of model identification, the effectiveness of the identified models is judged and then the nominal model is selected based on knowledge of the process by answering three questions: (1) Is the discrepancy between the model structures identified reasonable? (2) What are the causes for the discrepancy? (3) Which one should be used as the nominal model structure in control system design?

To answer the questions, one should first understand that the underlying process is actually a time-varying system, rather than a time-invariant system. As can be seen in both Figs. 7 and 8, although the average peak current and the base current are constant during welding, the produced output is higher when the welding has just begun. This implies that the relationship between the input and the output varies during welding along the weld seam. That is, the dynamic model of the controlled process varies. Of course, this variation in the dynamic model is understandable because, when the welding begins, the work-piece is at room temperature. However, as the welding proceeds, the temperature of the work-piece gradually increases and the same peak current would take less time to establish the keyhole. Hence, the system to be controlled is actually a time-varying system even though all the manufacturing conditions are nominally constant along the weld seam. As a result, it is only an approximation to use a time-invariant model to describe the controlled process.

Further, data sets 1 and 2 are produced from two experiments. Although the statistical characteristics of the two input sequences for the two experiments are the same, the size of data set 1 is approximately twice that of data set 2. If the system were time-invariant, the size of the data set would still make a difference in model identification but would not be as significant as from (2,2,1) to (5,3,1). However, if a time-varying system is approximated, longer data would result in a higher order model. Hence, it is reasonable that a discrepancy exists between two models identified using two different sets of data. The time-varying dynamics and the difference in the data size are responsible for the discrepancy.

Now the question is what model structure should be used in control system design. It is suspected that the
high order of the autoregressive part may actually be caused by the time-varying characteristic of the underlying process. Because this paper intends to establish the foundation for the control of quasi-keyhole process under different manufacturing conditions, the system must identify the model parameters on-line whenever application and manufacturing conditions change. This implies that the high autoregressive order caused by the time-varying characteristic may be reduced because of the recursive estimation. Hence, the autoregressive order should be reduced to the lowest in the two models. Further, the time-varying characteristic may also cause a higher moving-average order. In addition, Fig. 10 shows that the data set 1, which gives the (5,3,1) model, can also be described using the (2,2,1) model. As a result, (2,2,1) will be used as the model structure for control system design. The identified (2,2,1) model parameters will be used as the nominal or the a priori model parameters in the control system.

5. Control algorithm

Because it has been used successfully in controlling other welding processes (Zhang, Kovacevic, & Li, 1996), generalized predictive control (GPC) (Clarke, Mohtadi, & Tuffs, 1987), which is capable of controlling plants with variable parameters, variable dead-time, and variable orders, is selected for the underlying process described by

\[
y(k) = c_0 + a_1 y(k - 1) + a_2 y(k - 2) + b_1 u(k - 1) + b_2 u(k - 2) + c_1 I_b(k - 1) + e(k).
\]

The application of GPC to the above model is straightforward and the detailed derivations can be seen in Liu (2001). The following standard steps are considered necessary in order to describe the algorithm.

The first step toward describing the control algorithm is to simplify the model. For a specific application, the base current is fixed at a predetermined value and remains constant during control. Denote \( \tilde{c}_0 = c_0 + c_1 I_b \). Then \( \tilde{c}_0 \) can be considered as a constant and can be determined using the nominal values of \((c_0, c_1)\), as identified from the off-line experiments or directly identified on-line. Hence, the model reduces to

\[
A(q^{-1})y(k) = \tilde{c}_0 + b_1 u(k - 1) + b_2 u(k - 2) + e(k),
\]

where \( q^{-1} \) is the back-shift operator, and \( A(q^{-1}) = 1 - a_1 q^{-1} - a_2 q^{-2} \).

The second step is to solve the Diophantine equation

\[
AE_j + q^{-J}F_j = 1
\]

for \( E_j = 1 + e_1 q^{-1} + \cdots + e_{j-1} q^{-(j-1)} \) and \( F_j = f_{j,0} + f_{j,1} q^{-1} \).

In the third step, the recursively computed coefficients \((f_{j,0}, f_{j,1}, e_1, \ldots, e_{j-1})\) from solving the Diophantine equation are used to generate the following prediction equations:

\[
\hat{y}(k + 1) = (f_{1,0} + f_{1,1} q^{-1}) y(k) + [\tilde{c}_0 + b_1 u(k) + b_2 u(k - 1)]
\]

\[
\hat{y}(k + 2) = (f_{2,0} + f_{2,1} q^{-1}) y(k) + (1 + e_1 q^{-1}) [\tilde{c}_0 + b_1 u(k + 1) + b_2 u(k)]
\]

\[
\hat{y}(k + j) = (f_{j,0} + f_{j,1} q^{-1}) y(k) + (1 + e_1 q^{-1} + \cdots + e_{j-1} q^{-(j-1)}) [\tilde{c}_0 + b_1 u(k + j - 1) + b_2 u(k + j - 2)]
\]

Then in step four the desired trajectory \( y_d(k + i) \) is generated from the set-point sequence \( y_0(k + i) \) using a simple first-order lag model with a smoothing factor \( x \):

\[
y_d(k + i) = x y_d(k + i - 1) + (1 - x) y_0(k + i)
\]
with the following initial
\[ y_s(k) = y(k), \]  
where \( y(k) \) is the feedback of the output. It is known that a larger \( x \) corresponds to a lower speed but better robustness (Clarke et al., 1987).

Fifth, the control action is determined by minimizing the following cost function:
\[
J = E \left\{ \sum_{i=1}^{N_t} \left[ (y(k + i) - y_s(k + i))^2 + \lambda (u(k + i) - l)^2 \right] \right\} 
\]
\[ = \sum_{i=1}^{N_t} [(\hat{y}(k + i) - y_s(k + i))^2] 
+ \lambda (U - I_{iden})^T (U - I_{iden}) \]  
\[
(10)
\]
where \( I_{iden} = [I_c, I_c, \ldots, I_c] \in \mathbb{R}^{N_c \times 1} \) is a \( N_c \times 1 \) vector and \( U = [u(k), u(k + 1), \ldots, u(k + N_t - 1)]^T \) is the control vector consisting of the current and future control actions, \( N_t \) is the prediction horizon which is the maximum step of the predictions and needs to be determined based on the nominal open-loop response, \( \lambda \) is the weighting coefficient of the penalty on the deviation of the control action (peak current) from a specified current value \( l_c \). In this paper, \( N_t = 10 \) is selected. Before the cost function is optimized, a positive integer \( N_e \leq N_t \) known as the control horizon or the number of the free control actions \( (u(k), u(k + 1), u(k + 2), \ldots, u(k + N_e - 1)) \), needs to be determined. Many applications have used \( N_e = 1 \) (Montague, 1986; Zhang et al., 1996) because of its good robustness. Hence, this paper optimized the cost function with \( u(k) = u(k + 1) = \cdots = u(k + N_t - 1) \) and produced the following control algorithm:
\[
u(k) = \frac{\lambda N_t I_c - (\Gamma_N Y + \hat{e}_0 \Xi_{N_c} I_{N_c} + b_2 \hat{e}_2 u(k - 1) - Y_s)^T \Lambda}{\lambda N_t + \Lambda^T \Lambda},
\]
where
\[ \Gamma_N = \begin{bmatrix} f_{1,0} & f_{1,1} \\ f_{2,0} & f_{2,1} \\ \vdots & \vdots \\ f_{N_c,0} & f_{N_c,1} \end{bmatrix}, \]
\[ Y = [y(k), y(k - 1)]^T, \]
\[ \Xi_{N_c} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & e_1 & \cdots \ 0 \\ \vdots & \vdots & \vdots \\ 1 & e_1 & \cdots \ e_{N_c - 1} \end{bmatrix}, \]
\[ I_{N_c} = [1, \ldots, 1]_{1 \times N_c}^T, \]
\[ \hat{e}_2 = [1, e_1, \ldots, e_{N_c - 1}]^T, \]
\[ Y_s = [y_s(k), \ldots, y_s(k + N_t - 1)]^T, \]
\[ \Lambda = b_1 \Xi_{N_c} I_{N_c} + b_2 \Xi_{N_c - 1} I_{N_c - 1}, \]
\[ I_{N_c - 1} = [1, \ldots, 1]_{1 \times N_c - 1}. \]

Finally, during closed-loop control, a pre-designed random sequence is applied as the input during the beginning period. The duration of the beginning period varies from experiment to experiment in the range of from 35 to 40 weld cycles. During this period, the parameters are estimated using the nominal model’s parameters as the initials. However, the on-line estimated parameters are not actually used in the control algorithm until this beginning period ends. Simulation suggests that 0.95, 0.9, and 0.7 are acceptable values for the forgetting factor \( \gamma \) in the recursive least-squares algorithm, the penalty weight of the control action \( \lambda \) in (10), and the smoothing factor \( \alpha \) for the desired output transition trajectory in (8), respectively. As can be seen

![Fig. 11. Simulation of closed-loop control system: (a) system output; (b) control action.](image-url)
in Fig. 11, using these parameters, no significant steady-state errors are observed and the regulation speed is acceptable. Hence, those parameters and the forgetting factor will be used in the GPC algorithm and the recursive identification algorithm for control experiments.

6. Control experiments

The developed control algorithm has been used to conduct closed-loop control experiments under variable set-point and variable travel speed. The material used in the experiments is stainless steel (type 304). The thickness of the plate is 3.2 mm and the dimensions of the work-piece are 250 mm in length and 50 mm in width. The sampling period is the pulse cycle which consists of the fixed base current duration 420 ms and the variable peak current duration. Pure argon is used as the shielding gas and the orifice gas. The travel speed is 2 mm/s for all experiments except for the varying travel speed experiment.

In all the closed-loop control experiments, the model parameters are estimated using the nominal model’s parameters as the initials during the beginning period which varies from experiment to experiment in the range of from 35 to 40 weld cycles. The on-line estimated parameters replace that of the nominal model after the beginning period.

6.1. Open-loop experiment

Before the closed-loop control experiments were conducted, an open-loop experiment was done with a constant input \( I_p = 115 \) A. Fig. 12 depicts the corresponding output. As can be observed, despite the constant input peak current, the resultant output peak current period fluctuates in addition to a shift with time. This suggests that the controlled process is subject to an inherent disturbance.

Analysis shows that this disturbance is not caused by any external sources. Instead, it is in the controlled process itself. In fact, as shown in a previous study (Zhang & Ma, 2001), when the keyhole is being established, the process is in an unstable state. It is believed that during this unstable period, the geometry of the partial (non-penetrated) keyhole experiences a strong fluctuation as determined by the balance between the surface tension, the plasma pressure, and the hydrostatic pressure before the keyhole is finally established. The establishment of the keyhole is thus subject to a certain stochastic vibration or fluctuation. This inherent vibration or fluctuation creates an obstacle for establishing control of the keyhole arc welding process.

6.2. Varied set-point

The varied set-point is designed to verify the response speed of the GPC control system. The step set-point change is applied from 210 to 150 ms at the 100th weld cycle. The resultant output and control variable are

![Fig. 12. System output \( T_p \) under a constant peak current \( I_p = 115 \) A.](image)

![Fig. 13. Closed-loop control under set-point step change: (a) output; (b) control action.](image)
plotted in Fig. 13(a) and (b), respectively. As can be seen, the output $T_p$ can track the set-point change with an acceptable speed and accuracy. The response speed and accuracy are similar to those in the simulation.

Of course, fluctuations are observed in the output in Fig. 13. However, these fluctuations in the output are similar to those in the open-loop experiment and are caused by the inherent disturbances of the process. It appears that the inherent disturbance of the process has not had significant influence on the system’s performance.

6.3. Varying travel speed

The travel speed and the welding current are the two most important welding parameters determining the heat input into the work-piece (Zhang & Kovacevic, 1998). In this experiment, the travel speed changes from 2.18 to 2.47 mm/s at the 69th cycle, then from 2.47 to 3.2 mm/s at the 138th cycle, then back to 2.47 mm/s at the 142th cycle, and finally to 2.73 mm/s at the 154th cycle. Because of the large change in the speed, large disturbances are suddenly applied.

The output and control action after the speed increase at 69th cycle can be seen in Fig. 14. It is known that an increase in the travel speed will cause a longer time for a given peak current to establish the keyhole. Hence, in order to maintain the output, i.e., the peak current period at the desired set-point, the peak current should increase. As can be seen in Fig. 14(b), after the speed is increased at $t = 69$ cycle, the peak current keeps increasing. As a result, the influence of the travel speed increase on the output is minimized. Of course, because of the large increase in the travel speed, the parameters in the model are greatly changed. This sudden change in the model parameters will greatly affect the dynamic behaviors of the closed-loop control system. However, as can be seen in Fig. 14, except for a large impact on the control action right after the travel speed is changed at the 69th cycle, the control action responds smoothly.

Between $t = 138$ and 154, the speed is first increased to 3.2 mm/s from 2.47 mm/s at $t = 138$, then changed back to 2.47 mm/s at $t = 142$, and finally increased to 2.73 mm/s at $t = 154$. In this case, large speed impacts and changes are applied as artificial disturbances. These large impacts and changes caused large fluctuations in the control action. However, the output only briefly fluctuated below the set-point. It appears that the system quickly “realized” its “over-reaction” and rapidly corrected the “mistake.” As a result, after a brief period of fluctuation, the control action became smooth again. Of course, the fluctuations in the control action were actually caused by the sudden changes in the model parameters. Because of the large fluctuations in the control action and the resultant fluctuations in the output, the estimates of the parameters quickly converged to the new values so that the model and the control action became accurate and smooth again.

7. Conclusions

Keyhole arc welding has all the advantages of arc welding processes over laser welding. As a keyhole process, it has the potential to achieve deep narrow penetration like laser welding to minimize heat input, distortion, and material properties degradation. However, to reach its full potential, the process must be controlled. A promising method is to switch the current from the high peak current to the low base current after the keyhole is established, i.e., to use a quasi-keyhole method. Because the effectiveness of the quasi-keyhole method relies on the peak current, the amplitude of the peak current must be automatically adjusted.

A fundamental part of this research was to convert the weld quality assurance problem into a feedback control problem. To this end, two discrete-time variables, i.e., the amplitude and duration of the peak current, were defined based on an analysis of the quasi-keyhole process and its signal waveforms. The
controlled process was thus defined as a system which has these two discrete-time variables as the input and output. An adaptive control algorithm was then developed to automatically adjust the peak current in order to achieve the desired peak current duration.

Closed-loop control experiments under step set-point change and large travel speed changes and impacts have verified the effectiveness of the developed control system and the acceptability of the proposed process model structure, the adoption of the predictive control method for the quasi-keyhole process, and the simulation based selection of the design parameters including the forgetting factor $\gamma$, the penalty weight of the control action $\lambda$, and the smoothing factor $\alpha$ for the desired output transition trajectory. Moreover, the open-loop experiment has shown that the controlled process possesses an inherent stochastic disturbance. Fortunately, the effect of this disturbance in the closed-loop control response has been successfully suppressed. Because of the significant advantages associated with the keyhole arc welding process, the control system developed in this study is of practical interest and the authors are currently working on its practical applications.

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