

## **Nonlinear Robust Control of Keyhole Establishment Process Under Unknown Speed and Thickness**

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### **Introduction**

Quasi-keyhole arc welding, including controlled keyhole plasma arc welding (PAW) and double-sided arc welding (DSAW), switches the current from the peak to base level after the keyhole is established in order to prevent burn-through. Since switching occurs after the establishment of the keyhole, full penetration is guaranteed. Although a high peak current assures the establishment of the keyhole, excessive arc pressure blows liquid metal away from forming continuous weld. An appropriate peak current establishes the keyhole in an appropriate period. In this study, the peak current is adjusted so that the keyhole be established in a desired period.

### **Procedure**

The peak current and keyhole establishment period are the input and output of the feedback control system to be developed. To design the control algorithm, a dynamic model is needed to correlate the output to the past input and output. Four experiments are conducted to generate input-output data pairs on 4.7 mm and 6.7 mm thick stainless steel 304 plates using both 2 mm/s and 4 mm/s as the travel speed and four models are obtained. The parameters associated with different terms in the four models are used to determine the lower and upper limits for each term. The lower and upper limits for all the terms define an interval model. An interval model based robust control algorithm is then developed to control the quasi-keyhole PAW process.

## **Results and Discussion**

It is found that to predict the output, nonlinear terms of the products of the past input and output are needed in addition to linear terms. The use of the nonlinear interval model in the control system design significantly improves the performance and robustness of the feedback control system. In particular, closed-loop control experiments have been done by applying a step change of the travel speed from 2 mm/s to 4 mm/s. Despite the sudden change in the travel speed, the peak current is automatically adjusted to a new level so that the keyhole establishment period returns back to the set-point. Experiments with thickness step change also confirm that the peak current automatically adjusts to a new level so that the keyhole establishment period returns back to the set-point.

## **Conclusion**

The developed robust control system can automatically adjust the peak current to an appropriate level to achieve the desired keyhole establishment period without the knowledge of the thickness and travel speed. This suggests that the developed control system is robust against the variations in the manufacturing conditions. Also, the nonlinear interval model based control algorithm is found to be responsible for the robustness and performance of the developed system.

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