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Technical Paper

A comparison of model predictive control and PID temperature control in friction stir welding

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ABSTRACT

Temperature control of friction stir welding (FSW) via model predictive control (MPC) is investigated in Al 7075-T7. Two MPC controllers are compared against two well-tuned PID controllers to obtain a direct comparison of MPC and current FSW controllers. One MPC controller uses a first-order plus dead-time (FOPDT) model derived from a simplified conduction-advection view of the stir zone. The other MPC controller uses the Hybrid Heat Source model that describes heat conduction in the plate and tool.

At quasi steady-state conditions, all four controllers can easily hold temperature within 2 °C of the setpoint in the absence of large disturbances. Once the weld is past the initial traverse, the FOPDT controller is superior to the Hybrid Heat Source controller with regards to modeled-disturbance rejection and setpoint changes. The FOPDT controller is competitive with well-tuned PID controllers in this region of the weld. During the initial traverse, the Hybrid Heat Source controller and PID controller with regulator gains were able to control temperature within 5 °C of the setpoint, compared to a typical deviation of 20–30 °C when uncontrolled. During this period, the FOPDT controller and PID controller with servo gains could not maintain satisfactory temperature control.

MPC is demonstrated to be a viable control method for FSW. Temperature control before reaching steady state for both MPC and PID is shown to be feasible, but more difficult than for steady state. Recommendations are given for when each controller might be preferred in various circumstances, based upon the results shown herein.

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1. Introduction

Friction Stir Welding (FSW) is a solid-state joining process for metals. In FSW, a rotating non-consumable tool is plunged into and traverses along the joint between workpieces. The tool rotation against and within the workpieces generates significant heat which softens the metal. This allows the tool to stir the metal workpieces together and create a joint. When done properly, FSW can result in exceptional post-weld properties [1–3].

FSW is a temperature dependent process where important weld properties depend on staying within a thermal process window. FSW was originally implemented on modified milling machines where temperature was sometimes measured but never controlled; consequently temperature fluctuated over the course of a weld [4].

Early versions of temperature control often used spindle speed as the manipulated variable to control temperature [5]. Various methods have been used to measure the temperature of the stir zone [6–8]. When using a thermocouple, putting an embedded thermocouple closer to the tool-plate interface dramatically reduces the time delay of the system [5,8] and can thus improve control. By controlling temperature and other welding parameters, weld quality can be maintained despite external disturbances on the system [9,10].

An important advance in temperature control came with power control systems and better system identification and tuning for controllers. Temperature was controlled with a "cascade" approach: power was used to control temperature within a slower outer loop, and a quicker inner loop was used to control power itself [8,11]. Ross used spindle power and a PID controller to control the temperature of welds within 2 °C [8,12]. Both Ross and Marshall identified FSW as a primarily first-order plus dead-time (FOPDT) system. Marshall used a relay feedback test to determine FOPDT system parameters and calculated PID gains using tuning rules [13]. He was able to maintain temperature within 2 °C, obtained better

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settling characteristics than Ross's early work [8,12], and had good disturbance rejection properties.

Model Predictive Control (MPC) is a control method that is well suited for multivariate control of large-scale and complex systems [14]. MPC uses a system model that predicts the impact of input changes on the output parameters, and an optimizer uses this information to manipulate the input parameters for optimal control of the output parameters. MPC has been successfully used in different industries for many years [15–17].

Cederqvist and Nielsen developed nonlinear models for welding out-of-round copper canisters and focused on depth and force control. Using these models they performed simulations for nonlinear multiple-input multiple-output (MIMO) MPC control of depth and temperature [18,19]. Their work showed very significant theoretical promise, but has thus far focused on process simulation for the evaluation of controllers.

Recently, two other FSW models have been developed, namely a FOPDT model and a more complex Hybrid Heat Source model [20,21]. These models have acceptable temperature predictions based upon spindle power and traverse speed when used after the initial transient of a weld. Based upon these temperature prediction capabilities, an MPC controller using these models is expected to perform well so long as the gains and time constants of the models are close to that of the actual process [22].

The objective of this investigation is first, to confirm that MPC is a viable control scheme in actual welding (as opposed to simulation), and second, to compare MPC to other controllers to determine which have superior performance in a variety of circumstances. Accordingly, this paper evaluates two MPC controllers in-process and compares them against well-tuned PID controllers. Based upon performance, recommendations are made as to which controllers perform best in which circumstances.

2. Controller selection and setup

2.1. The need for different comparison controllers

When comparing multiple methods or types of controllers to each other (i.e., MPC vs PID), multiple tuning methods help to provide an unbiased comparison. Otherwise, if poor tuning was unwittingly performed, the poor resultant control might be errantly assumed to have been caused by the controller type (i.e., MPC or PID), rather than due to poor tuning.

Consequently, for both MPC and PID, two variants were chosen and carefully tuned. For MPC, two different models were derived to capture different fundamental physics of the process, and model parameters were chosen for each by curve fitting step test data. For PID, "servo" and "regulator" tuning rules were chosen, and system identification was performed via an automatic relay test. All controllers command power (via a torque command) [23] in order to control temperature.

2.2. Quasi-PRBS tuning welds

In order to determine parameters for the models, several welds were performed in 6.4 mm (0.25″) thick 2.44 m (8′) long Al 7075-T7. After the start-up sequence, the heat input and traverse speed were abruptly and semi-randomly changed to one of three possible levels and were held at that level for a random length of time. This approach is similar to a Pseudo Random Binary Sequence (PRBS), but three levels of heat input and traverse speed were used to enable the detection of nonlinearity. These step tests were performed at a nominal temperature of 440 °C, and nominal travel speed of 3.8 mm/s (9 ipm) (Fig. 1).

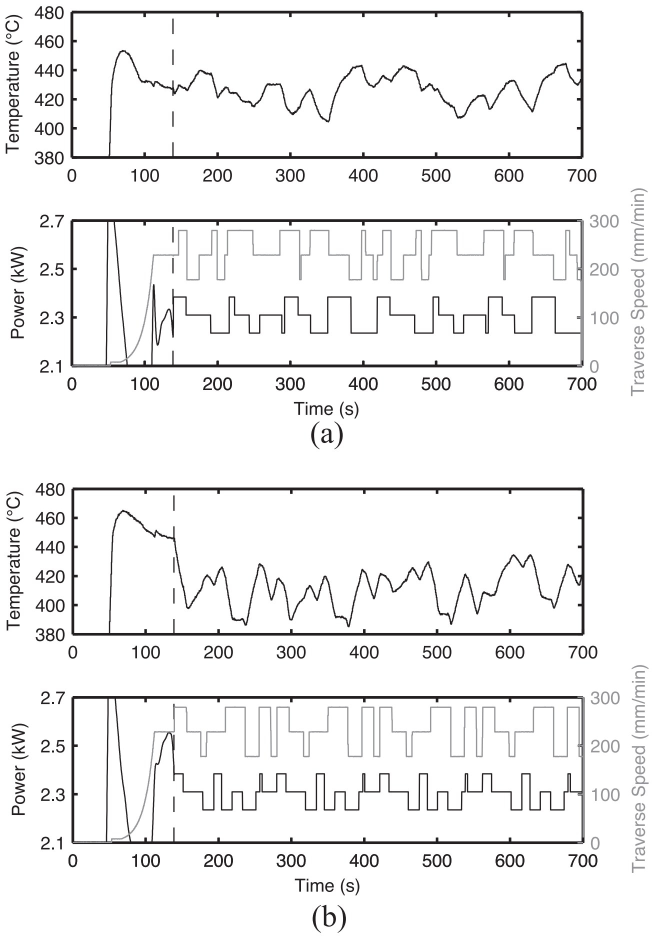

Fig. 1. Temperature, power, and traverse speed for the welds used to tune the FOPDT and Hybrid Heat Source controllers. The vertical dashed line indicates the start of the PRBS section of the weld. Power and traverse speed sequences were repeated twice in (a), and four times in (b).

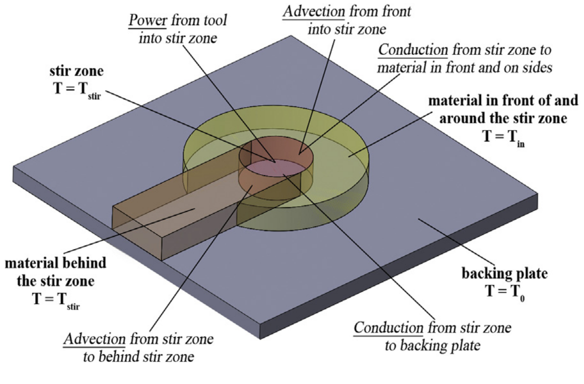

Fig. 2. Regions of the first-order model that interact with the stir zone (bold text), and modes and approximate locations of energy transfer between the stir zone and the other regions (underlined and italicized text).

2.3. The FOPDT model for MPC

The FOPDT model is derived by approaching FSW from a control volume of the stir zone perspective [20,21]. Heat conducts out through the plate, tool, and weld anvil, and material advects through the stir zone. This is shown schematically in Fig. 2. Based upon simulation results, a controller based upon the FOPDT model is expected to perform well after the initial traverse segment of the weld [21].

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