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Technical Paper

Dynamic modeling of friction stir welding for model predictive control

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ABSTRACT

Controlling temperature in Friction Stir Welding (FSW) is important for consistent post-weld properties. PID temperature control of FSW has been previously implemented once the process is at a quasi-steady state, but has not worked well during either starting transients or during process changes that significantly alter the system dynamics. This work develops models and theories for the application of Model Predictive Control (MPC) to FSW and assesses temperature predication capabilities in simulation.

Two different model forms are developed for MPC and are evaluated in simulation. The first model is a first-order plus dead time (FOPDT) model. The second is the Hybrid Heat Source model that combines the heat source method and a 1D discretized thermal model of the FSW tool. Model parameters are determined by fitting model predictions to weld data. This is done both manually and via optimization-based curve fitting. The models' fits are compared quantitatively by calculating the mean-subtracted SSE (MSSSE) and average absolute derivative error. The manually tuned parameter sets result in a better fit by both metrics for both models. The FOPDT model matches the post-startup-transient data better than the Hybrid Heat Source, and is expected to have superior control in this region of the weld. The Hybrid Heat Source model is expected to have superior temperature control during the startup transient.

1. Introduction

Friction Stir Welding (FSW) is a solid-state hot-deformation process that is used to join two pieces of metal. In this process a tool is rotated and pushed into the seam of two work pieces (the plunge). This action creates heat and softens the metal. Once the metal is sufficiently soft, the tool starts traversing; slowly at first, then transitioning to full speed (the traverse ramp). Once at full traverse speed, the tool continues to travel along the seam of the two pieces and joins them by stirring the metal together. Significant thermal transients are present during the plunge and traverse ramp, and often persist after a constant traverse speed is reached. Because FSW does not melt the weld zone, post-weld properties such as strength, ductility, and fracture toughness are much better than in traditional welding [1,2].

FSW was first implemented by selecting a depth, travel speed, and spindle rotation speed; these methods have been used successfully for many years [3,4]. However, if a weld is run at constant input parameters, the temperature in the weld may fluctuate over time due to transients and disturbances. Because FSW is an inherently temperature-dependent process, if the temperature in the weld is too high or too low, the strength and quality of the weld is negatively affected. In some cases, the welded piece is completely unusable if temperature control is poor [5].

Recently, work has been done to actively control weld temperature [6,7]. Ross [3,8] used a PID controller to control temperature, with tool temperature as the output variable, and power to the rotating tool as the input variable. Ross also showed that directly controlling the motor torque to achieve a set power – and letting the rotational speed float – is an effective means of controlling power. This method of controlling power is consequently used for all models presented in this paper. Marshall [9,10] refined the process of determining PID gains by using a relay feedback test to perform system identification and then used established PID gain rules [11]. Both authors were able to control weld temperatures in both aluminum and steel within one degree Celsius [3,8–10].

PID controllers do not perform well in the presence of large initial errors or in highly transient situations. Due to the significant thermal transients present during and immediately after the start of a weld, controlling temperature with a PID controller has been difficult.

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Nielsen [12,13] has done significant theoretical work in controlling FSW for the sealing of nuclear waste copper canisters. In this application, the machine compliance is non-trivial, and the machine must be capable of welding out-of-round copper cylinders. For these reasons, Nielsen focused heavily on weld depth and axial forces as process variables.

Nielsen developed three different empirical controllers from PRBS weld data. Two controllers were based upon decentralized axial force and depth models, and these in turn were used to tune PI and PID controllers. Using a PI controller, a few welds were performed with good success. Nielsen also developed a full model for non-linear MPC. Nielsen's MPC model is composed of three separate cross-connected models for depth, temperature, and torque. While this controller performed very well against other controllers in simulation, no MPC welds were actually performed. MPC is a proven control technique that has been successfully applied to a variety of fields [14–16] and several different welding processes such as GMAW [17] and GTAW [18–20] and is consequently expected to work for FSW as well.

This study seeks to build upon prior work by developing models for MPC that are able to account for thermal transients, and that consequently have better control during significant transients and disturbances. Physics based models are developed and then tuned using time-series FSW data. The models fit the data well, and it is expected that using both models for MPC will result in good control.

2. Model development

A sufficiently accurate model is necessary for MPC to make accurate move predictions over the control horizon. An accurate model leads to accurate predictions, and good control follows [15].

Attempts to model FSW have ranged from empirical approaches including modified Computational Fluid Dynamics (CFD) programs [21–24]. All attempts have been able to capture some trends, but have been unable to accurately model all important aspects of FSW. However, in order to control temperature, the MPC controller's model needs only to predict the temperature changes relative to changes in system input(s).

In this investigation, two heat transfer based models are considered. The first is a simple first-order plus dead time (FOPDT) model. Both Ross and Marshall noted that the dynamic temperature response of FSW to power step inputs is approximated well by a FOPDT system [8–10]. The second model is a modified heat source method coupled with a thermal 1D tool Finite Element Analysis (FEA). The heat source method uses a history of point heat sources to calculate the temperature at any point and time within a semi-infinite solid, and the hybrid model couples this with a 1D thermal FEA of the tool.

2.1. First-Order Plus Dead Time model

The FOPDT model is based on a simplified thermal view of FSW with different regions of the weld providing for the major heat transfer modes via conduction and advection, as shown in Fig. 1. While these regions do not precisely match reality, an approximate model is often adequate because model parameters are adjustable and can be used to compensate for inaccuracies. Table 1 lists all terms used in the development of the model. In this model, power is the input, temperature is the output, and velocity is used as feed forward variable.

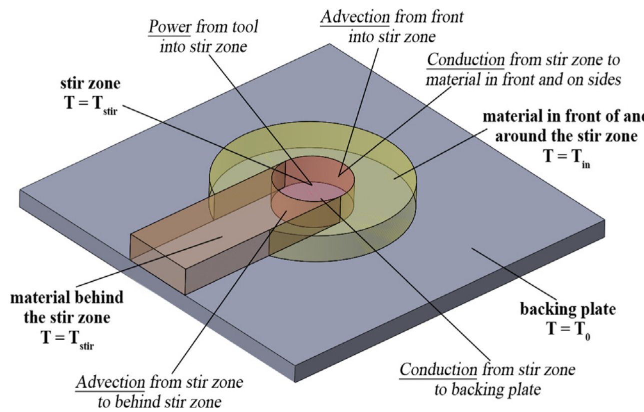

Fig. 1. Regions of the first-order model that interact with or are the stir zone (bold text), and modes and approximate locations of energy transfer between the stir zone and the other regions (underlined and italicized text).

Table 1
Definitions of terms in the FOPDT model.

Term	Definition
A	Area of metal advecting through stir zone (m^2)
E_{in}	Net energy into the stir zone (J)
P	Spindle/tool power (W)
Q_{adv}	Advection power into the stir zone (W)
Q_{cond}	Conduction power into the stir zone (W)
Q_{tool}	Power into the stir zone from tool (W)
T_{stir}	Temperature of the stir zone (°C)
T_0	Temperature of the room/backing plate (°C)
T_{in}	Temperature of metal entering stir zone (°C)
a, b, c, d	Weighting parameters
h_1, h_2	Convection coefficients (W/m^2 °C)
c_1	Power parameter (°C/kW)
c_2	Linear velocity parameter (°C s/m)
c_3	Quadratic velocity parameter (°C s^2/m^2)
c_4	Environment parameter (°C)
c_p	Heat capacity of metal (J/kg °C)
m	Mass of stir zone (kg)
$\dot{m}$	Mass flow rate through stir zone (kg/s)
ρ	Density of metal in the stir zone (kg/m^3)
τ	Time constant of the system/stir zone (s)

The stir zone is predicted for the purpose of control. The basic dynamic temperature equation of the stir zone is:

$$\frac{dT_{stir}}{dt} = \frac{E_{in}}{m\, c_p} \quad (1)$$

There are three separate modes of energy transport/generation in the stir zone: heat generation due to tool rotation, conduction, and advection. Substituting these three terms for E_{in}, and recognizing that the total thermal capacitance of the stir zone is proportional to the time constant of the system, τ, Eq. (1) is equivalent to:

$$\tau \frac{dT_{stir}}{dt} = aQ_{tool} + bQ_{cond} + cQ_{adv} \quad (2)$$

2.1.1. Assumptions

All regions are assumed to be isothermal. The backing plate and weld anvil reservoir temperature, T_0, is assumed to be a constant 25 °C. The backing plate and anvil system are of sufficient thermal mass as to be relatively unaffected by weld thermal energy and consequently heat transfer between them and the room is negligible for the time periods of a friction stir weld. Heat loss up the tool is either ignorable and/or can be lumped together with the backing plate. The geometry and thermal material properties of the regions do not change with temperature or travel speed, and thus the model parameters do not change with these. The measured temperature in the tip of the tool is representative of the temperature of the