Available online at www.sciencedirect.com

ScienceDirect

Manufacturing Letters 5 (2015) 7–11

www.elsevier.com/locate/mfglet

Research Letter

Physics-based interpretation of tool-workpiece interface temperature signals for detection of defect formation during friction stir welding

Amber Shrivastava, Clemens Dingler, Michael Zinn, Frank E. Pfefferkorn *

Department of Mechanical Engineering, University of Wisconsin–Madison, USA

Received 19 August 2014; accepted 12 April 2015
Available online 5 May 2015

Abstract

The objective of the work is the reduction and eventual avoidance of post welding inspections that are currently needed to ensure defect-free welds. An analytical thermal model of the FSW process along with an analytical disturbance model is developed. This disturbance model relates defect formation to variations in the measured temperature and is based on experimental process identification. A dynamic disturbance observer computes an estimate of the disturbance signal, which is further processed in order to provide information about the presence of defects along the weld. Experiments for one kind of disturbance verify that the observer shows good tracking behavior.

Keywords: Friction stir welding; Temperature; Control; Defect

1. Introduction

Friction stir welding (FSW) was invented at The Welding Institute (TWI) of UK in 1991 [1]. The advantages of friction stir welding (FSW) are significant, including energy savings, superior joint mechanical properties, and lower process environmental impact as compared to other welding processes [2–4]. However, while FSW is an inherently cost-effective welding process, the need for significant weld inspection, particularly in the case of high-reliability applications, can increase the cost of FSW by a factor of three or more, making it cost-prohibitive. Therefore, a new approach to weld inspection is required – where characterization of weld quality can be obtained in real-time, drastically reducing the need for post-process inspection. The objective of this work is to create a FSW defect detection approach using physics-based process and defect dynamic modeling. The use of process and defect dynamic models to filter or condition the measured process outputs significantly improves the detection. Analytical thermal model, disturbance model and disturbance observer developed for this work are explained below.

1.1. Thermal process model

A physics-based thermal process model was developed that relates process inputs (*i.e.*, tool rotation frequency, f [Hz] and traverse speed, v) to the measured process output (*i.e.*, tool-workpiece interface temperature). The thermal process model uses a transient, lumped-parameter approach. Fig. 1 shows a sketch of the thermal model. For this model m_{SLZ} represents the mass of shear layer zone (SLZ) which rotates with the spinning tool, T_{SLZ} is the temperature of the SLZ, $\dot{m}_{\mathrm{i}}$ and $\dot{m}_{\mathrm{o}}$ are mass flow in and mass flow out rates, and q_{gen}, q_{ao}, q_{ai} and q_{c} are heat

---

* Corresponding author. Tel.: +1 608 263 2668.
E-mail address: frank.pfefferkorn@wisc.edu (F.E. Pfefferkorn).

http://dx.doi.org/10.1016/j.mfglet.2015.04.002
2213-8463/

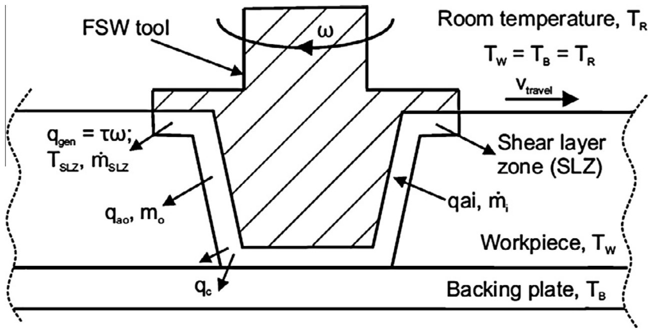

Fig. 1. Schematic of the lumped-parameter thermal model.

generated due to plastic deformation in SLZ, heat advected out with mass flowing out, heat advected in with mass flowing in and heat conducted out to work piece and backing plate, respectively. It was assumed that: all the energy from the spindle is converted to thermal energy, *i.e.*, $q_{\text{gen}} = \tau\omega$, where τ is torque and ω is angular tool rotation speed; workpiece and backing plate temperatures are constant and equal to room temperature, T_{R}, *i.e.*, $T_{\text{W}} = T_{\text{B}} = T_{\text{R}}$; no flash is generated during welding; convection and radiation heat losses to the surroundings are negligible; heat loss through the FSW tool is negligible; and thermo-physical properties are constant, uniform, and evaluated at a representative temperature of 400 °C.

For this system, conservation of energy and mass for the SLZ was written as:

$$m_{\text{SLZ}} c_{\text{SLZ}} \frac{dT_{\text{SLZ}}}{dt} = q_{\text{gen}} + q_{\text{ai}} - q_{\text{ao}} - q_{\text{c}} \tag{1}$$

$$\dot{m}_{\text{i}} - \dot{m}_{\text{o}} = \dot{m}_{\text{SLZ}} \tag{2}$$

Substituting $q_{\text{gen}} = \tau\omega$, $q_{\text{ai}} = \dot{m}_{\text{i}} c_{\text{w}} T_{\text{w}}$, $q_{\text{ao}} = \dot{m}_{\text{o}} c_{\text{SLZ}} T_{\text{SLZ}}$, and $q_{\text{c}} = S_{\text{w}} k_{\text{w}} (T_{\text{SLZ}} - T_{\text{R}}) + S_{\text{b}} k_{\text{b}} (T_{\text{SLZ}} - T_{\text{R}})$ into Eq. (1) yielded:

$$\begin{aligned} m_{\text{SLZ}} c_{\text{SLZ}} \frac{dT_{\text{SLZ}}}{dt} &= \tau\omega + \dot{m}_{\text{i}} c_{\text{w}} T_{\text{w}} - \dot{m}_{\text{o}} c_{\text{SLZ}} T_{\text{SLZ}} \\ &\quad - S_{\text{w}} k_{\text{w}} (T_{\text{SLZ}} - T_{\text{R}}) - S_{\text{b}} k_{\text{b}} (T_{\text{SLZ}} - T_{\text{R}}) \end{aligned} \tag{3}$$

where c_{SLZ} and c_{w} are specific heat of the SLZ and the workpiece, respectively, k_{w} and k_{b} are thermal conductivity of the workpiece and the backing plate, respectively, and S_{w} and S_{b} are shape factors for a vertical cylinder in a semi-infinite medium and a disc on a semi-infinite medium, respectively [8]. $\dot{m}_{\text{i}}$, S_{w} and S_{b} are calculated from tool geometry, travel speed and tool rotation frequency. q_{gen} is directly proportional to m_{SLZ}, and ω was held constant in experiments, therefore,

$$m_{\text{SLZ}} = K\tau \tag{4}$$

such that,

$$K = \frac{m_{\text{SLZ-s}}}{\tau_{\text{s}}} \tag{5}$$

where $m_{\text{SLZ-s}}$ is mass of the SLZ and τ_{s} is torque, while at steady state. $m_{\text{SLZ-s}}$ is calculated as per [9] and τ_{s} is determined later in this section (Eq. (14)).

To cast the equations into a more convenient form, the state variable, x and input variable, u are defined as:

$$x = \frac{T_{\text{SLZ}}}{\tau} \tag{6}$$

$$u = \frac{1}{\tau} \tag{7}$$

Substituting Eqs. (2), (4), (6) and (7) into (3), and collecting constants together,

$$\frac{dx}{dt} = (C - Bx + Au)u \tag{8}$$

where A, B and C are constants given by:

$$A = \left(\frac{\dot{m}_{\text{i}} c_{\text{SLZ}} + S_{\text{SLZ}} k_{\text{SLZ}} + S_{\text{b}} k_{\text{b}}}{K c_{\text{SLZ}}} \right) T_{\text{R}} \tag{9}$$

$$B = \frac{\dot{m}_{\text{i}}}{K} + \frac{S_{\text{SLZ}} k_{\text{SLZ}} + S_{\text{b}} k_{\text{b}}}{K c_{\text{SLZ}}} \tag{10}$$

$$C = \frac{\omega}{K c_{\text{SLZ}}} \tag{11}$$

T_{SLZ} is the process output given by:

$$T_{\text{SLZ}} = \frac{x}{u} \tag{12}$$

Eqs. (8) and (12) represent the nonlinear thermal process model. Torque in Nm and steady-state temperature in °C for a good weld were identified as functions of two FSW process inputs: tool rotation frequency, f in Hz and traverse speed, v in mm/min using the experimental data from [5]. The functions are:

$$\begin{aligned} \tau = 1.96 &+ \frac{358.53}{f} + 0.37v - \frac{812.53}{f^2} \\ &- 0.000016v^2 - 0.43\frac{v}{f} \end{aligned} \tag{13}$$

$$\begin{aligned} T_s = 520.29 &+ \frac{2432.58}{f} + 0.34v - \frac{23396.18}{f^2} \\ &- 0.000092v^2 - 8.25\frac{v}{f} \end{aligned} \tag{14}$$

Equations (13) and (14) have coefficients of determination (R^2) of 0.962 and 0.952, respectively. Steady-state torque was given by Eqs. (6)–(8) as:

$$\tau_s = \frac{BT_s - A}{C} \tag{15}$$

1.2. Defect model

A reduction in the SLZ mass from its steady state value indicates the formation of a defect. Therefore, a disturbance model was established to estimate the SLZ mass deviation from steady-state, Δm. The ratio of the output, T_{SLZ}, and the state variable, x, from the process model gives the estimated torque. The difference in the estimated torque and the experimentally identified torque for good welds was related to the SLZ mass deviation from steady-state using Eq. (4). The disturbance model for Δm [kg] is given by: