International Journal of Heat and Mass Transfer 76 (2014) 411–418

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Inverse determination of heat input during the friction stir welding process

Ching-yu Yang

Department of Mold and Die Engineering, National Kaohsiung University of Applied Sciences, Kaohsiung city 807, Taiwan, ROC

ARTICLE INFO

Article history:
Received 16 February 2014
Received in revised form 15 April 2014
Accepted 16 April 2014
Available online 22 May 2014

Keywords:
Friction stir welding
Inverse heat conduction

ABSTRACT

Determining the input heat required to achieve a satisfactory standard during the friction stir welding (FSW) process is a novel study. This study proposes a computational method for predicting an appropriate heat input during the FSW process to reduce the effect of heat-induced defects caused by heat response. The method was deduced from a finite element method based on an inverse algorithm. No preselected functional form for an unknown function and no sensitivity analysis are required in the algorithm. One example was used to demonstrate the characteristics of the proposed method. The numerical results indicated that the predicted heat input is adequate for the welding process.

1. Introduction

Friction stir welding (FSW) is a solid joining technology that was invented in 1991 [1]. It produces high-quality welds in materials with such as aluminum, nickel, and steel [2,3], and is widely implemented in the automobile, aerospace, and shipbuilding industries, particularly for manufacturing lightweight transport structures [4,5].

During FSW, a rotating cylindrical shoulder tool with a profiled pin is transversely fed between the weld pieces to be joined. The mechanical energy of the rotating tool is transferred to heat by the wear-resistant welding components and welding pieces. This heat is generated from friction between the tool and material, and a temperature response is induced in the welding pieces. The heat generated joins the material as well as influences the temperature behavior of the material. The heat transfer modeling of FSW progressed considerably in the recent two decades [6–35]. Russell and Shercliff [6], Gould and Feng [7], and Feng et al. [8] have adopted simplified heat inputs instead of heat generation by using tools during FSW. Chao and Qi [9], Ulysse [10], and Khandkar [11] have used a three-dimensional (3D) finite-element model to study temperature distribution during the FSW process. Frigaard et al. [12,13] used a finite-difference technique to calculate the multidimensional thermal fields during FSW. Song and Kovacevic [14] proposed a 3D FSW numerical model in which a heat source is attached to a moving coordinate. Nandan et al. [15,16] numerically simulated heat transfer and plastic flow during 3D FSW. A substantial amount of research has focused on estimating the amount of heat generated [9,11–13,17–19]. Chao and Qi [9] used a trial-and-error procedure to adjust the heat input at the interface of a tool shoulder and workpiece until the calculated temperatures agreed with the measured temperatures in a 3D heat transfer model. Frigaard et al. [12,13] adjusted the friction coefficient to ensure that the melting point was attained during the FSW process. Colegrove et al. [17], Mijajlović and Milčić [19], and Schmidt and Hattel [18] have used an analytical estimation of heat generation on the welding tool. Khandkar et al. [11] estimated torque as a source of heat input.

Solidification cracking, porosity, and solute redistribution can be prevented during FSW because the liquid phase does not cool in the joint materials; however, other problems can occur when using FSW. Some problems with FSW are inadequate heat input and inadequate material plasticity caused by long tunnel-like defects and poor continuity of the bond between materials. The phenomena of heat input and material plasticity can be inferred in the temperature response of the joint material, which is a critical parameter for ensuring a high quality of welds in FSW. Kim et al. [20] stated that an abnormal temperature behavior during FSW causes defects such as a large mass of flash, a cavity, or a groove in the shape of the stir zone.

Based on the previous discussion, a satisfactory temperature distribution is favorable for achieving a high-quality weld. Therefore, it is necessary to develop a novel method for estimating an appropriate heat input to reduce the heat-induced defects. The aforementioned literature review indicated that research on FSW

E-mail address: cyyang@cc.kuas.edu.tw

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.04.036
0017-9310/

Nomenclature

$[A]$	conductivity matrix	ρc	heat capacity per unit volume
$[B]$	transient matrix	Δt	increment of temporal domain
$[C]$	$\frac{1}{\Delta t}[K]^{-1}[B]$	ϕ^{q,i_q^j}	unknown heat flux condition at i_q^jth grid
$[D]$	inverse matrix of $[K]$	$\boldsymbol{\theta}$	vector from previous state and the present known boundary
e	intermediate variable	Ω	sensitivity matrix
k	heat conductivity	$\boldsymbol{\Phi}$	vector from ϕ^{q,i_q^j}
$[K]$	$[A]+\frac{1}{\Delta t}[B]$	$[\bullet]$	matrix
h	convection heat transfer coefficient	$\{\bullet\}$	column vector
q_n	heat flux	$\lfloor\bullet\rfloor$	row vector
$\{R\}$	boundary vector		
$\{R^0\}$	vector of the known boundary condition	*Subscripts*	
$\{R^q\}$	vector of the unknown heat flux boundary	i, j, k, l, m, n	indices
t	temporal coordinate	$x, y, z, up, down, amb$	indices
T	temperature	n_q	number of unknown grids of heat flux boundary
$\{T\}$	temperature vector	n_p	number of grids at spatial coordinate
$\{\dot{T}\}$	derivative of the temperature vector, $\{\frac{dT}{dt}\}$	p	number of preselected temperature at spatial coordinate
$\lfloor u^i \rfloor$	unit row vector with a unit at i-component		
$\{u^\bullet\}$	unit column vectors with a unit at •th component	*Superscripts*	
V	general spatial domain	i, l, n	indices
v	tool moving speed	i_q^j	grid number of the estimated flux function
x, y	spatial coordinate		
Y	preselect temperature		
α, β, γ	intermediate variables		

has disregarded the role of heat input prediction. Thus, to help fill this gap in our knowledge, this study developed an inverse algorithm [36,37] to determine an appropriate heat input for FSW.

In this study, the joining temperature was increased to improve the plastic forming workability, and an appropriate heat input was predicted to melt the material in the vicinity of a pin during a constant FSW process. A numerical method was proposed to solve the problem and used to predict the input sequentially without sensitivity analysis. Moreover, using the proposed method, a closed-form was derived using the numerical model to represent the unknown explicitly. The heat input and the temperature coordinate were then determined step by step.

This paper comprises six major sections. Section 2 provides background information on the current development of heat transfer during FSW and the features of the proposed method; Section 3 details the characteristics of the inverse problem and describes the process of the proposed method; Section 4 briefly outlines the computational algorithm for computers; and Section 5 presents an application of FSW and discusses the analyzed results. Finally, Section 6 concludes the paper and details the contribution of this study as well as provides suggestions for future development.

2. The proposed sequential method for the suitable heat input

2.1. Problem statement

The problem is to find an appropriate heat input during FSW with constant transverse speed (see Fig. 1) and the melting temperature is set at the material surface on contact with the pin. The pin of the rotating tool is insert into the weld piece. During FSW process, the rotating tool moves along the weld joint and the front of weld piece melted down by the friction heat. In concise terms, a moving coordinate system referred to the tool axis is adopted [14]. It is a convection–conduction heat transfer problem and the equation is shown as follow:

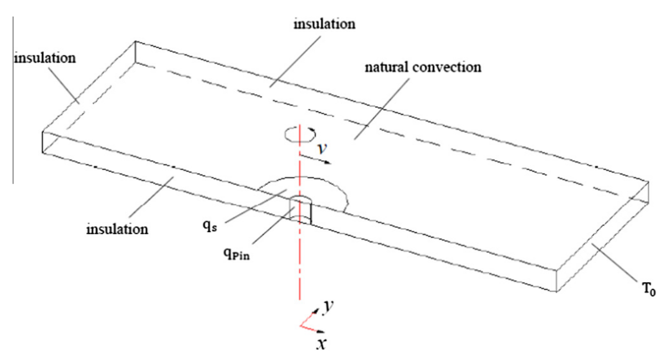

Fig. 1. Friction stir welding model.

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right)+v\frac{\partial(\rho cT)}{\partial x} = \frac{\partial(\rho cT)}{\partial t} \qquad (x_i, y_i)\in V \tag{1}$$

where T is the temperature, c is the heat capacity, ρ is the density, k_x, q_s and k_z are the heat conductivity, and v is the tool moving speed.

The boundary condition is shown in Fig. 1 and the plate is initially at a uniform temperature T_0. Due to symmetry, the thermal insulation along the welding line is set. The back side surface is adiabatic and right side surface is isothermal. The upper and lower surface of the weld piece is cooled by natural convection with coefficient h_{up} and h_{down} respectively. The corresponding expressions are $q_{up} = h_{up}(T_{amb} - T)$ and $q_{down} = h_{down}(T_{amb} - T)$. T_{amb} is ambient temperature and there is no heat change at the melting part of weld piece. The undetermined problem is to estimate the amount of heat input (i.e., q_s in Figure one) that is adequate to satisfy the tool movement requirement and to prevent heat-induce weld defect.