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Research Paper

A BFGS and simple step method for estimating the interface temperature in 2D ultrasonic seam welding

Thi-Thao Ngo [a], Jin H. Huang [b], Van-The Than [c], Chi-Chang Wang [b,*]

[a] Faculty of Mechanical Engineering, Hung Yen University of Technology and Education, Khoai Chau District, Hung Yen Province, Viet Nam
[b] Department of Mechanical and Computer-Aided Engineering, Feng Chia University, No. 100 Wenhwa Rd., Seatwen, Taichung 40724, Taiwan, ROC
[c] Ph.D. Program of Mechanical and Aeronautical Engineering, Feng Chia University, No. 100 Wenhwa Rd., Seatwen, Taichung 40724, Taiwan, ROC

HIGHLIGHTS

- An inverse BFGS Method is presented for finding heat generation in an USMW.
- The computational procedure without sensitivity analysis is proposed.
- The proposed method has a high efficiency, lower iterations and high accuracy.
- Estimations agree well with exact values even considering measurement error.
- Strongly provide good information for the optimization of a welding problem.

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ABSTRACT

An inverse method for estimating unknown interface heat generation in an ultrasonic seam welding process based on a combination of the Broyden–Fletcher–Goldfarb–Shanno (BFGS) and Simple Step Method is presented. In this study, a nonlinear direct problem is solved by using the Hybrid Spline Difference Method (HSDM). Heat generation and interface temperature, which are extremely difficult to directly measure, can be determined inversely through the Direct Problem, Adjoint Problem, and the Simple Step Method without sensitivity analysis. Special features of proposed method are stable, accurate, and efficient for estimating moving heat sources and interface temperature even including measurement error. The predicted interface heat generation and temperatures are in very good agreement with exact solutions for different heat sources profiles. Furthermore, the influence of the measurement location on the accuracy of estimated solutions with or without error of measurement was also discussed. These findings indicate that the estimated heat generation is more sensitive than the temperature to different measured errors and locations. According to analysis of results, the occurrence of thermal defects can be avoided during the welding process. In addition, the proposed method strongly provides good information for optimization of the welding process.

1. Introduction

Ultrasonic metal welding (USMW) is applicable for welding almost all metal specimens successfully and is used for joining similar and dissimilar metal parts in various manufactures as well as industries by applying a high ultrasound frequency vibration and normal pressure. The vibrations with high frequency generate heat at the joint interface of the two parts being welded, creating a solid-state weld under the pressure. The major advantages of this welding technique over other conventional welding processes are a low heat input at the weld and a very short completion time. The welding temperature in the welded zone is lower than the melting temperature of materials needed to be welded. Due to low temperature, residual stresses in parts made with USMW are significantly reduced, and the different thickness metal specimens can be welded together. Furthermore, in the ultrasonic welding, the specimens are connected without use of filler metals and adhesive materials.

Heat generated during USMW is a major area of interest because it mainly decides temperature distribution in the welding zone. The temperature is the most significant element in deciding the quality and the price of welding products. If we can know and control the temperature during the welding operation then the

* Corresponding author.
E-mail address: chicwang@fcu.edu.tw (C.-C. Wang).

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Nomenclature

$\mathbf{A}$	Hessian matrix
a	temperature-dependent factor of $k(T)$
b	temperature-dependent factor of $C_p(T)$
$C_p(T)$	heat capacity, (J/kg °C)
$\mathbf{E}$	updated matrix
f_w	welding frequency, (Hz)
F_N	normal force, (N)
h	convection heat transfer coefficient, (W/m^2 °C)
$\mathbf{I}$	unit matrix
J	object function
∇J	gradient of object function
$k(T)$	thermal conductivity, (W/m °C)
M	number of temperature measurement points
N	number of unknown parameters
$\vec{\mathbf{P}}$	search direction
$q_w(x,z)$	unknown heat generation, (W/m^3)
x, z	coordinates
$T(x,z)$	temperature, (°C)
V_w	speed of welding, (m/s)
$\vec{\mathbf{W}}$	unknown vector

Greek symbols

α	heat conversion factor
β	search step size
δ	thickness of workpieces, (m)
λ	Lagrange function
σ	standard deviation of measurement error, (°C)
ρ	density, (kg/m^3)
ξ_0	sonotrode amplitude, (µm)

Superscripts

k	value of last iteration
i, j	value at grid spatial points

Subscripts

exact	exact value
inv	inverse solution
m	measurement point
w	properties at the weld interface
∞	properties for ambient temperature

welding conditions can be completely adjusted and optimized. Therefore, an estimation of heat generation during the entire welding process plays a very important role in the ultrasonic welding and in other welding processes as well. Recently, the inverse methods in heat transfer problem have been studied and applied for finding accurate heat flux, characteristics of the materials or interface temperatures, etc. Direct heat conduction problems involve the calculation of temperature distributed in the workpieces when knowing the heat generated at the interface, the thermo-physical properties and the initial as well as boundary conditions; whereas, the inverse heat conduction problems concerned with estimation of energy, thermo-physical properties, convection heat transfer coefficient, etc., from given measurement temperatures taken on the welding tool or sample's subsurface.

Because of incomplete understanding of heat transfer in the USMW, several authors have studied heat propagation at the contact surfaces during an ultrasonic welding process. Koellhoffer et al. [1] measured the temperature values of USMW by using an infrared (IR) camera and employed Finite Element Analysis to forecast welding temperatures. An effect of frictional coefficient on the heat generated at the welding interface was reported. The welding conditions, such as normal force, amplitude, and speed, affected the increase in temperature were also presented [2]. It was shown that the vibration amplitude was the most influential in inducing a higher temperature. A 40% increase in amplitude raising the temperature by almost an equal proportion (about 36%) was reported. The steady state temperature focused entirely on welding zone was also recorded by using the IR camera [3]. Besides, Sriraman et al. [4] used thermocouples embedded at the central seam of the tape to record the generated temperatures which depended on the height of processed layer. Resulting from the possible reducing in ultrasonic energy dispersing to the welding area, the authors have found a decrease in temperature with increasing built height. A small K-type thermocouple was embedded at the interface between two tapes under various combinations of vibration amplitude and clamping force using different similar and dissimilar metal specimens for obtaining the measured temperatures [5]. At the interface, the peak temperature was found depending on the welding parameters. Thus, the measuring temperature is an important task in a lot of research. However, in order to directly measuring temperature in the contact zone is extremely difficult, even impossible, and very few studies have been done through a solution of inverse problem. Lately, based on given measurement temperature at some locations on the workpiece, Huang et al. [6] have successfully determined heat generation and its distribution range in ultrasonic welding; also, Ngo et al. used an inverse method to estimate the interface temperature and convection coefficient in 1D ultrasonic welding [7] as well as the temperature-dependent thermophysical properties of the material [8]. Nowadays, various analytical and numerical methods have being applied to solve the inverse problems. An application of the conventional inverse technique and Finite Element Method are used to find the boundary condition of heat flux and temperature, generated heat, and root temperature on the various shaped fins [9–11]. Several ways to solve direct problem and optimization algorithm have been applied for finding solution of the inverse heat transfer problem; they are the Finite Difference Method, Finite Element Method [12,13], Conjugate Gradient Method (CGM) [14–20], the Least-Square Method [21,22] and the Steepest Descent Method (SDM) [23]. Especially, a combination of the mechanical ANSYS parametric design language and the CGM was established to estimate time-dependent heat sources in a high speed spindle [24]. Furthermore, the BFGS algorithm, developed for solution of the optimization problem, attained good numerical performance and acceptable results in the inverse heat conduction problem [25], and for a nonlinear least squares problem [26]. Similarly, L-BFGS-B was used for solving box constrained optimization programs [27]. In addition, the BFGS method was also applied in the ultrasonic welding for determining heat sources as well as welding temperatures rapidly [6,7].

The proposed inverse algorithm in this research is a numerical method that can predict unknown heat generation and interface temperature without sensitivity analysis. In this study, a two-dimensional mathematical model of USMW was established for solving the direct problem with a known-boundary condition. Then, the exact solutions which were the solutions of the direct problem were entered into an inverse process to estimate generated heat and distribution of temperature based on the measured temperature on the workpiece subsurface through the BFGS in collaboration with the Steepest Descent Method and the Simple Step