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Inverse determination of laser power on laser welding with a given width penetration by a modified Newton–Raphson method ☆

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ABSTRACT

In this paper, the inverse determination of the laser power in welding process with a given width penetration using the modified Newton–Raphson method (MRN) is presented. The advantage of this inverse method does not adopt the nonlinear least-squares error to formulate the inverse problem, but it is implemented a direct comparison between the known melting temperature and the computed melting temperature. The isothermal elliptic shape at the bottom surface is considered, and two "auxiliary" variables including a semi-major axis and an elliptic center are added into the formulation. Two examples are used to demonstrate the proposed method. The results shows that the proposed method is an accurate and robust method to inversely estimate the laser power for a given width penetration.

1. Introduction

Laser welding is recognized as an advanced technology to join materials with a laser beam of high-energy density, high power. Compared with the conventional welding process, laser welding offers a number of attractive characteristics such as high efficiency, minimal heat affected zone (HAZ) and low distortion. By these good features, laser welding can fabricate a wide range of joints of plastics or metal ranging from very thin sheet of about 0.01 mm thickness to thick plate of about 50 mm. Thus, the applications of laser welding have been broadened in many industrial production, especially for micro-joining as assemble and packaging MEMS [1].

As a result, solving laser welding-related problems have been main objective of many scientists in the past decades. Many studies presented the analytical and numerical models to predict the heat distribution and thermal cycles of welding process. Based on fundamental theory of heat flow for moving heat source, Rosenthal [2] first suggested the analytical model with point or line heat source. However, Rosenthal's model is subjected a serious error for temperature in or near weld pool. To overcome these drawbacks, Pavelic et al. [3] and Friedman [4] used the disc model with Gaussian heat distribution on the workpiece surface combining with the finite element method (FEM). The results showed that the temperature distribution in the weld pool was dramatically achieved, comparing with Rosenthal's model. After that, Goldak et al. [5–7] proposed a double ellipsoidal volume heat source, which is considered as flexible model for various cases in welding process. For the deep penetration welding, the volume heat source with Gaussian conical profile of the laser beam is used [8,9]. These analytical and numerical models are based on the heat conduction-based models. Studies showed that the laser welding process is very complex because the weld pool geometry is influenced by both heat transfer and fluid flow in the fusion zone. The convective heat transport-based models, which take into account the melt pool convection due to buoyancy and thermocapillary forces, are considered to accurately predict the weld pool shape and temperature distribution [10–13]. Nevertheless, these convective heat transport-based models require much greater expertise and higher time-consuming computation than the normal heat transfer models [14]. Thus, for small weld pool size and rapid melting, the heat conduction-based models are often applied thanks to simpler and computationally inexpensive [15].

Besides, researchers investigated the effects of laser welding parameters on the weld size and quality. Batahgy [16] studied the effects of laser welding parameters on fusion zone shape and solidification structure of austenitic stainless steels. The results showed that the increase in welding speed caused a rise in the ratio of weld depth to width, while the penetration depth increased with the rise in laser power. Benyounis et al. [17] used the response surface methodology (RSM) to investigate the effects of laser power, welding speed, and focal point position on the heat input, the weld penetration, welded zone width and heat affected zone width. Based on the Box–Behnken design, a mathematical model for predicting weld-bead geometry was developed. One of the main results is that the heat input plays important role in the weld-bead parameters dimension. The influence of beam incidence angle in the laser welding of Austenitic Stainless Steel was evaluated by Shanmugam et al. [18]. The result reveals that the depth of penetration-to-width ratio decreases in increase of the beam incident angles. By using a three-dimensional

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Nomenclature

a	semi-major axis
C	heat capacity
k	thermal conductivity
h	heat convection coefficient
f	weight fraction
L	heat latent
P	laser power
N	number of equations
M	number of variables
T	temperature
T_l	melting temperature
T_s	solidus temperature
$\dot{q}$	the volume heat source
v	welding speed
x,y	Cartesian coordinates
t	thickness of sheet
w	width penetration (= semi-minor axis of ellipse)
x_c	the elliptic center
r_b	the laser beam radius

Greek symbols

$\mathbf{\Phi}$	vector constructed from $\mathbf{\Phi}$
$\mathbf{\Phi}_c$	calculated temperature
$\mathbf{\Phi}_m$	known melting temperature
$\boldsymbol{\chi}$	variables vector
$\mathbf{\Psi}$	sensitivity matrix
β	thermal expansion coefficient
ε	emissivity coefficient
δ	value of the stopping criterion
ρ	density
ξ	Cartesian coordinate
η	absorption coefficient
Δ	increment of the search step

Superscripts

i,j,t,u,v	indices
k	iterative step
T	transpose of matrix

finite element method combining with experimental results, Frewin et al. [19] showed that temperature profiles and weld pool geometry are strong functions of both focal position and beam incidence angle.

From the above results, it can be concluded that the weld pool geometry depends on the laser power, welding speed, focus position, and the beam incident angle. Some authors performed the optimization of theses process variables for several certain welding cases by using the algorithms such as genetic algorithm, artificial neural network, and Taguchi based on experimental data [20–22]. These obtained results showed that the laser power is the most importance parameter that the weld penetration as well as joint quality deeply depend upon the laser power [23]. In particular, for micro butt joint or lap joint with very thin sheet, the low laser power results in the unfull penetration, while high laser power causes the material lost due to the vaporization. These unfit laser powers result in a poor welding quality. The establishment of appropriate laser power for prior known joint configuration and some given parameters, like welding type, laser beam diameter, and welding speed, is thus necessary to obtain the high quality of joints. However, none of previous published papers can propose the effective method to determine the laser power for some given parameters and known welding configurations until now.

In this paper, a novel method to inversely determine the laser power with a given width penetration using a modified Newton–Raphson method (MNR) is presented. The finite element method is used for solving the nonlinear heat transfer equation based on the conduction-based model. MRN is utilized to determine the laser power by minimizing the appropriate function representation. MNR has been applied successfully to solve the inverse problem as presented by Yang [24–28]. To demonstrate the validity and application of the proposed method, two examples are employed. The results show that the proposed method is potential and feasible in finding the appropriate laser power for some given parameters and known welding configurations.

2. Problem statement

The aim of this paper was to propose a new method based on the inverse algorithm to find an appropriate laser power during welding process with a given width penetration. To simplify, the heat conduction-based model and three-dimensional double ellipsoid proposed by [6] are considered as Fig. 1. Based on the principle of conservation of energy, the three-dimensional heat conduction equation for laser welding process with moving heat source along the welding line can be expressed as follows:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}=\rho C\frac{\partial T}{\partial t} \tag{1}$$

Because the laser beam moves with a constant velocity v (say, in x-direction), a moving coordinate system is defined as (ξ, y, z), where $\xi = x - vt$. In the quasi stationary regime, the heat conduction Eq. (2) become as follows:

$$\frac{\partial}{\partial \xi}\left(k\frac{\partial T}{\partial \xi}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}=\rho C\, v\frac{\partial T}{\partial \xi} \tag{2}$$

where k, ρ, and C refer respectively to thermal conductivity, density, and specific heat of the workpiece material; $\dot{q}$ is the volumetric heat source defined as follows:

$$\dot{q}\,(\xi,y,z)=\frac{6\sqrt{3}f_{1,2}\eta P}{a_{1,2}bc\pi\sqrt{\pi}}\exp\left(-3\frac{\xi^2}{a_{1,2}}-3\frac{y^2}{b^2}-3\frac{z^2}{c^2}\right) \tag{3}$$

where, η and p are the absorption coefficient and the laser power, respectively; f_1 and f_2 denote the weight factions with the front and rear ellipsoids ($f_1 \sim 0.6$ for front side and $f_2 \sim 1.4$ for real side); and a_1, a_2, b, and c are the parameters of the double ellipsoid volume heat source.

The boundary is shown in Fig. 1. Due to symmetry, the thermal insulation along the welding plane is set. The rear side surface is adiabatic, and front side surface is isothermal. The other surfaces of the weld piece are cooled by natural convection and radiation:

$$-k\frac{\partial T}{\partial n}=h(T-T_0)+\sigma\varepsilon\left(T^4-T_0^4\right) \tag{4}$$

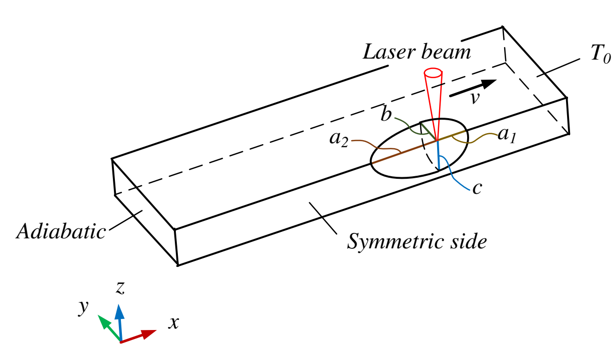

Fig. 1. The laser welding model with the double ellipsoid volume heat source [6].