Materials and Design 92 (2016) 246–260

Contents lists available at ScienceDirect

Materials and Design

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

Simulation and experimental study of laser transmission welding considering the influence of interfacial contact status

Huixia Liu *, Wei Liu, Dongdong Meng, Xiao Wang

School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, China

ARTICLE INFO

Article history:
Received 17 October 2015
Received in revised form 7 December 2015
Accepted 11 December 2015
Available online 12 December 2015

Keywords:
Laser transmission welding
Thermal contact model
Volumetric heat source
Interfacial contact status
Weld profile

ABSTRACT

The traditional finite element model (FEM) of laser transmission welding (LTW) is generally assumed that the interface of transparent and opaque materials is ideal. This assumption ignores the influence of real interfacial contact status on welding results. For this problem, the volumetric heat source model is constructed based on the Lambert–Beer law in this paper. And thermal contact model of LTW is constructed in the mode of volumetric absorption. Then the numerical simulation of temperature contours during LTW process is taken into thermal contact model. Under the condition of no interface gap ($S = 0$), the weld temperature contours and weld profile of transparent and opaque PA66 are obtained by numerical simulation and experiment. Furthermore, under the condition of interface gap ($S = 20$), the weld temperature contours and weld profile of thermal contact model are analyzed and predicted. The results show that thermal contact model is more consistent with real model when compared with traditional model. And thermal contact model can reasonably predict the changes of weld temperature contours and weld profile. Therefore, thermal contact model can be used to characterize the influence of interfacial contact status on welding results and improve the accuracy of numerical simulation in the process of LTW.

1. Introduction

The numerical simulation of laser transmission welding (LTW) can not only simulate the temperature contours of welding process, but also optimize the welding process parameters [1–3]. Furthermore, some of the mechanism and phenomena of welding process can be explained and predicted. Thus the numerical simulation is essential to the study of LTW. The traditional welding process parameters, including laser power, welding speed, laser spot diameter, laser energy distribution, carbon content, etc., are generally considered in the numerical model [4–7]. However, in addition to the above factors, interfacial contact status will also have a significant effect on welding results. In addition, the clamping force, the structure and the shape error of welding process will lead to the occurrence of interface gap, which will affect interfacial contact status, and then leads to different welding results.

In the aspect of interfacial contact studies, Dhorajiya [8] used interfacial contact model to simulate the temperature and stress contours of Ti and polymer, silicon and glass. Then the different temperature and stress contours of the upper and lower layers at the welding interface were obtained, and the weld width was predicted. Van de Ven et al. [9,10] established the two-dimensional temperature model of the heat source based on the finite volume method using MATLAB. The influence of interfacial contact status was considered, and then the variation of interfacial pressure in the welding process was simulated. Subsequently, the weld widths of PVC under the condition of two kinds of gaps were predicted using this model. Taha et al. [11] established a three-dimensional (3D) model using surface heat source, which was based on the finite volume method. And the influence of clamping force on the weld profile was analyzed by using the interfacial contact model. In the aspect of interface gap studies, Chen et al. [12,13] established the analytical solution model of LTW, and predicted the maximum bridge clearance. Meanwhile, the effect of different welding parameters and material properties on the gap bridging capability was explored. Kihara et al. [14] studied gap welding using the method of “absorption control welding (ACW)”, and proved that this method can significantly improve the gap bridging ability. Masse [15] directly formed various types of gap patterns on the surface of welding components, and then explored the sensitivity of LTW to gap.

The above studies have important significance for scholars to deeply understanding the impact of interfacial contact status and interface gap on welding process and results. Although the influence of interfacial contact status on temperature contours has been taken into numerical simulation, it still has limitation to predict weld width, and the reason is the lack of effective experimental verification. In addition, the influence of interface gap focusing on tensile strength of welding specimens is evaluated in terms of interface gap, but does not involve the weld profile. The previous studies about interfacial contact status are parts of the investigations of interfacial contact conduction, and the

---

* Corresponding author.
E-mail address: lhx@ujs.edu.cn (H. Liu).

http://dx.doi.org/10.1016/j.matdes.2015.12.049
0264-1275/

investigations of thermal contact model have just begun in LTW. It is necessary to further investigate the thermal contact conduction and thermal contact model in the process of LTW.

In the present study, the volumetric heat source model is established based on the Lambert–Beer law. And the heat source model can be used to obtain the temperature contours in the thermal simulation of LTW. In order to characterize the effect of non-ideal contact status on thermal conduction between both parts, the thermal contact conductance (TCC) is introduced into the thermal contact model of LTW. Then the thermal contact FEM of LTW is established to investigate the effect of interfacial contact status on the temperature contours theoretically. Furthermore, simulations and experiments are carried out for different gap-widths (0 and 20 μm) on the interface. In order to compare experimental results with simulated results, the heat affected zones (HAZ) are measured under different welding parameters. The dimensions of the HAZ are compared with the position of the melt isotherm. And when there is a gap (20 μm) between both parts, the nominal average value of TCC decreases, which means the deterioration of interfacial contact status. And then the measured and calculated HAZs are compared and analyzed. The introduction of the TCC and thermal contact model has great significance in improving the accuracy of thermal simulation in LTW.

2. Experimental equipment and materials

2.1. Experimental equipment

In this paper, a Compact 130/140 semiconductor continuous laser manufactured by DILAS is used for welding experiments. The maximum power of the laser device is 130 W, the output wavelength is 980 ± 10 nm and the optical fiber transmission is used. A three-axis motion system is used for the welding experiments and its measurement range is W300 × L300 × H200 mm. A self-made manual clamping device is used, and the clamping force can be measured and displayed by a force sensor. After experiments, the weld profile of all welding specimens is observed using 3D VHX-1000 microscopy, which is made by KEYENCE.

2.2. Experimental materials

The material employed in this study is DuPont Zytel® 101L NC010 PA66 manufactured by injection molding. The milky white and pure PA66 of the upper layer is used as laser-transparent component; the black PA66 of the lower layer is used as laser-absorbent component, where 0.2 wt.% carbon black (CB) is used as absorbent. The welding form is lap welding, and in order to ensure the uniformity of the clamping force, the upper and lower layers are clamped by the clamping fixture using K9 glass. The dimension of experimental material is 20 mm × 20 mm × 1.5 mm. In order to avoid the influence of burrs on interfacial contact status, cutting edge processing is needed before welding. A KQ3200E ultrasonic cleaning machine is used for cleaning the specimens before welding, and then the specimens are placed in a drying oven about 36 h.

3. Numerical model of LTW

In the process of modeling, the following hypothesis is made:

1) The construction of heat source model is based on the laser energy which arrives at the top surface of opaque PA66.
2) The heat source distribution on the top surface of opaque PA66 follows the Gauss distribution.
3) Isotropic material properties.
4) Laser beam diameter does not change during the propagation of laser beam in opaque PA66.

3.1. Introduction of thermal contact conductance

When the thermal conduction occurs between the two contact surfaces, the non-ideal contact status and the different thermal properties of both parts will cause the discontinuity of temperature on both sides of the interface. This discontinuity of temperature leads to the temperature difference (ΔT) on the interface [16,17]. The temperature difference further causes the thermal conduction. This phenomenon is called the thermal contact conduction. The resistance of the thermal conduction can be expressed as the thermal contact resistance (TCR), as defined by [17]:

$$\mathrm{TCR} = \frac{\Delta T}{q} \tag{1}$$

where $q(\mathrm{W/m^2})$ is the heat flow caused by temperature difference (ΔT) on the interface. The reciprocal of the TCR is defined as the thermal contact conductance (TCC) on the interface, which is given by:

$$\mathrm{TCC} = \frac{q}{\Delta T}. \tag{2}$$

In the thermal contact model, the TCC is generally used to describe the ability of thermal conduction across the contact interface. A number of experimental and theoretical investigations have been carried out, and varied theoretical models of interfacial contact conduction have been established [17–23]. Considering the effect of surface roughness, contact pressure, etc., the typical solid–solid thermal contact conduction was established by Zheng et al. [23]:

$$\mathrm{TCC} = \frac{\phi_2 k}{2\pi\psi} \cdot \frac{m}{\sigma} \exp\left\{-\left[erfc^{-1}\left(\frac{2P}{\phi_1(P+H)}\right)\right]^2\right\} \tag{3}$$

where k is the harmonic mean of the thermal conductance of the contact pair; ψ is the constriction alleviation factor; ϕ_1 and ϕ_2 are the accommodation plasticity index; m is the effective mean absolute slope of surface profile; σ is the effective root meat square surface roughness of both surfaces; *erfc* is the complementary error function; P is the contact pressure; and H is the Vickers micro-hardness.

In the process of LTW, there is difference between the mechanism of thermal contact conduction and solid–solid thermal contact conduction. The main reason of this difference is that the process of LTW involves the solid–liquid phase change. Thus the solid–solid thermal contact conduction cannot be used directly in LTW. However, the thermal contact model mainly describes the effect of non-ideal contact status on thermal conduction between both parts. And in the investigations of LTW, the interfacial contact status between both parts is also non-ideal on the interface. Therefore, by reference to the solid–solid thermal contact conduction (see Eq. (3)), the investigations of thermal contact conduction can be introduced into the LTW. And the TCR and TCC, used to characterize the thermal contact resistance and thermal contact conductance respectively, can be also introduced into the thermal contact model of LTW. Then through the introduction of the TCR and TCC, the effect of interfacial contact status on the welding results will be investigated theoretically.

During the process of the introduction of the TCC in LTW, the TCC is used to characterize whether the thermal conduction is easy or not between both parts, and the interfacial contact and interfacial pressure contribute to the thermal conduction. In the process of thermal conduction within the interface, thermal expansion directly determines the contact area and interfacial pressure. Therefore, thermal expansion indirectly affects the thermal conduction and thermal contact conductance on the interface. When there is a gap (20 μm) between both parts, the contact area and interfacial pressure decrease, and the effect of thermal expansion on the thermal conduction will be more obvious.