International Journal of Heat and Mass Transfer 90 (2015) 665–677

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Effects of interfaces on heat transfer in laser welding of electrical steel laminations

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ARTICLE INFO

Article history:
Received 18 January 2015
Received in revised form 4 July 2015
Accepted 4 July 2015

Keywords:
Electrical steel
Laser welding
Thermal contact conductance
Heat transfer

ABSTRACT

Laser welding is one of the most potential methods for joining of electrical steel laminations, which is commonly used in motor, transformer and compressor. Because of the existence of multiple interfaces in the welding path, the heat transfer in laser welding of the electrical steel laminations is significantly different from that in the normal welding. In this study, a finite element model (FEM) considering the effects of interfaces has been developed in ANSYS to analyze the heat transfer in laser welding of electrical steel laminations. The contact elements with birth and death options were used to describe both the existed and the vanished statuses of the interfaces during welding. The simulation results showed that the temperature distribution in the zone beside the interfaces was discontinuous at first and then changed to be continuous after the interface vanished. The highest temperature fluctuated periodically during the welding process because of the effects of multiple interfaces. The joint area decreased with the increase of sheet thickness but was robust with respect to the normal pressure applied on the sheets and the contact statuses of the interfaces to some extent. The estimated joint areas at various welding velocities were validated by experimental results. This work provides a better understanding of the heat transfer in laser welding of the electrical steel laminations.

1. Introduction

Electrical steel laminations have been widely used in motor, generator and transformer to deliver energy [1,2]. To reduce energy consumption, the sheet is designed to be thin (e.g. 0.18, 0.27 and 0.54 mm) and insulating coatings on both sides of the sheet are used to obstruct the eddy current excited by the alternating magnetic field [2,3]. The loose laminations are welded at the edge to ensure the strength [4]. Laser welding is one of the most potential methods for welding of electrical steel laminations because of concentrated heat source and small deformation [2,4]. Fig. 1 shows the schematic for welding of electrical steel laminations. Dozens of electrical steel sheets are laminated and welded with high power density laser beam. Metal near the center of the laser beam is fused and the adjacent sheets are joined. As joint area is a critical quality indicator of the welded laminations which affecting both the joint strength and the magnetic properties [5,6], it is important to analyze the heat transfer and provide a better understanding of the effects of the key parameters on the joint area.

Temperature distribution in laser welding of traditional structures has been extensively researched [7–15]. In these researches, the heat applied by the laser beam was simulated by the surface or body heat source model, the convection and radiation boundaries were defined to simulate the heat exchange between the coupons and the environment. The enhanced thermal conductivity of the fused metal was set to simulate the heat transfer caused by the flow of the liquid [8,14,15]. However, most of these work was based on the butt coupons or the lapped coupons [7,12]. Nearly no researchers had focused on the welding process of multiple laminations and effects of interfaces on heat transfer in welding had rarely been studied.

Fig. 2(a) shows the schematic of heat transfer at the surface of the weld seam and Fig. 2(b) shows that at the longitudinal section. At first, the interfaces in the welding path hindered the heat transfer. Then the partial interface vanished when metal beside the interface was melted and heat could go through the vanished interface freely. Thus, the interfaces had a significant effect on the heat transfer in welding of electrical steel laminations. To represent the heat transfer capacity of the interface, thermal contact conductance of the interface was defined in previous researches [16–18]. Mathematical model has been developed to calculate the conductance value [19–22] and various experiments were

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.07.027
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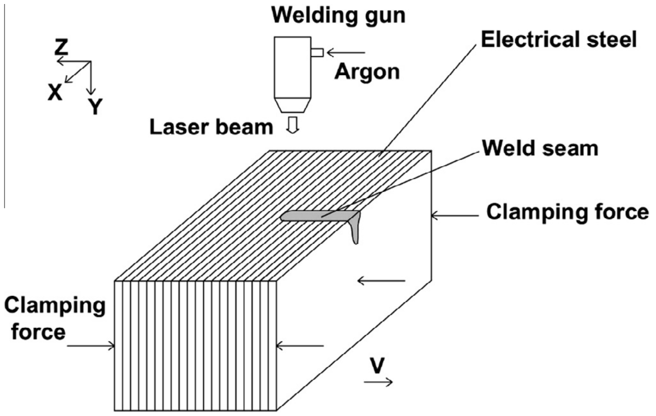

Fig. 1. Schematic for laser welding of electrical steel laminations.

conducted to validate the accuracy [23–26]. These researches provided a meaningful guide for modeling the effects of interfaces on heat transfer.

In this paper, a 3-D FEM has been developed in ANSYS to research the heat transfer in laser welding of the electrical steel laminations considering the interfaces effects. The contact elements with birth and death options were used to describe both the existed and the vanished statuses of the interfaces during welding [27]. The thermal contact conductance of the interface was calculated based on the existed mathematical model and a large enough thermal contact conductance value (e.g. 1.0e12 W/(m^2 °C)) was set to simulate the vanished interface. Both temperature distributions and joint features during the welding process were presented, and effects of thermal contact conductance, sheet thickness and welding velocities on the joint dimensions were discussed. This work provides a better understanding of the heat transfer in laser welding of the electrical steel laminations.

2. Modeling process

2.1. Assumptions

The assumptions made to simplify the FEM are as follows:

(1) Temperature distribution was thought to be symmetrical with the longitudinal section of the weld seam (plane *Y–O–Z* shown in Fig. 4). Only half of the geometry model was built and the symmetry boundary condition was set on the longitudinal section.

(2) The gaps between the laminations were neglected. The upper surface of the N^{th} sheet was modeled to have the same *Z* coordinate value as the lower surface of the $(N+1)^{th}$ sheet. The contact elements were used to simulate the effects of the interfaces.

(3) The partial interface vanished when temperature of the metal at the interface reached the critical interface vanishing temperature, which was assumed to be the mean value of solidus and liquidus temperature (shown in Table 2).

(4) The vanished interface was simulated by setting the thermal contact conductance with a large enough value, e.g. 1.0e12 W/(m^2 °C) in this paper.

2.2. Boundary conditions

2.2.1. Governing equation

Heat conduction in laser welding is non-uniform and rapid. Under the action of the concentrated heat source, the temperature of the laser applied region is beyond the boiling point of the metal. The spatial and temporal distribution of the temperature field fulfils the differential equation of three-dimensional heat conduction in a domain *D*, which is shown below [28]:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+Q=\rho C_s\left(\frac{\partial T}{\partial t}-v\frac{\partial T}{\partial z}\right) \quad (1)$$

where *x*, *y*, *z* are the coordinate values of the Cartesian coordinate system, *T* is the temperature (°C), *t* is the time (s), ρ is the material density (kg/m^3), C_s is the specific heat capacity (J/(kg °C)), **k** is the thermal conductivity (W/(m °C)), **Q** is the heat generation rate per unit volume (W/(m^3)) and **v** is the moving velocity of laser (m/s).

The initial condition of temperature distribution can be written as:

$$T(x,y,z,0)=T_0(x,y,z)\in D \quad (2)$$

where T_0 is the room temperature and is set to be 21 °C in this study. The thermal convection and thermal radiation boundary conditions can be expressed as:

$$k_n\frac{\partial T}{\partial n}-q+h(T-T_0)+\sigma\varepsilon((T+273.1)^4-(T_0+273.1)^4)$$
$$=0\ (x,y,z)\in S_1\ t>o \quad (3)$$

where S_1 represents the surfaces which are attached to imposed heat fluxes, radiation and convection, k_n is the thermal conductivity normal to boundary S_1 (W/(m °C)), h is the coefficient of thermal convection (W/(m^2 °C)), σ is the Stefan–Boltznann constant for radiation (5.67e^{-8} W/(m^2 °C^4)), ε is the heat radiation coefficient, *T* is the material surface temperature (°C), T_0 is the initial temperature (°C), *q* is the heat flux normal to boundary S_1 (W/m^2). Due to the

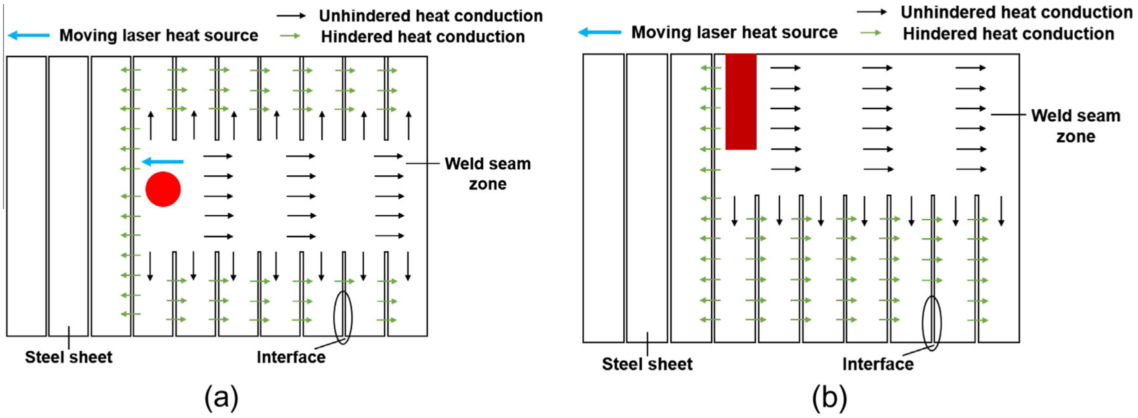

Fig. 2. Schematic of the heat conduction process: (a) at the surface of the weld seam zone; (b) at the longitudinal section.