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Three-dimensional transient thermoelectric currents in deep penetration laser welding of austenite stainless steel

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A R T I C L E I N F O

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A B S T R A C T

The existence of thermoelectric currents (TECs) in workpieces during the laser welding of metals has been common knowledge for more than 15 years. However, the time-dependent evolutions of TECs in laser welding remain unclear. The present study developed a novel three-dimensional theoretical model of thermoelectric phenomena in the fiber laser welding of austenite stainless steel and used it to observe the time-dependent evolutions of TECs for the first time. Our model includes the complex physical effects of thermal, electromagnetic, fluid and phase transformation dynamics occurring at the millimeter laser ablated zone, which allowed us to simulate the TEC, self-induced magnetic field, Lorentz force, keyhole and weld pool behaviors varying with the welding time for different parameters. We found that TECs are truly three-dimensional, time-dependent, and uneven with a maximum current density of around 10^7 A/m^2 located at the liquid-solid (L/S) interface near the front or bottom part of the keyhole at a laser power of 1.5 kW and a welding speed of 3 m/min. The TEC formed three-dimensional circulations moving from the melting front to solidification front in the solid part of workpiece, after which the contrary direction was followed in the liquid part. High frequency oscillation characteristics (2.2–8.5 kHz) were demonstrated in the TEC, which coincides with that of the keyhole instability (2.0–5.0 kHz). The magnitude of the self-induced magnetic field and Lorentz force can reach 0.1 mT and 1 kN/m^3, respectively, which are both consistent with literature data. The predicted results of the weld dimensions by the proposed model agree well with the experimental results. Our findings could enhance the fundamental understanding of thermoelectric phenomena in laser welding.

1. Introduction

Thermoelectric currents (TECs) caused by the Seebeck effect are generated when two junctions of a closed loop made by two dissimilar conducting materials are placed in different temperatures. TECs have long been known to play important roles in many industrial processes, such as in nuclear reactor boiling [1], electron beam welding [2–5], and directional solidification [6–8]. TECs are also found near the interaction zone during the laser welding process of metals [9]. Nevertheless, to the best of the authors' knowledge, there is currently a lack of reported research on the time-dependent evolutions of TECs in the high energy beam welding process.

TECs in high-energy beam welding process have been discussed and explored in previous research. Paulini et al. [3] proposed a simple analytical model for TECs in the electron beam (EB) and laser welding of two dissimilar metals. They numerically showed that a TEC at more than 100 A may occur in plates with a 20- or 30 mm thickness and a 0.1- to 1 mT magnetic field may be induced at the surface of the workpiece during the electron beam welding process. Wei et al. [4,10,11] experimentally and analytically investigated the thermoelectric magnetism (TEM) in the electron beam (EB) welding of dissimilar metals. They found that the TEC could reach around 104 A and the magnetic field could reach around 10 Gauss during the welding process. Moreover, Wei et al. were the first to derive possible influence factors for the TEM and EB deflection angles by scale analysis. Kern et al. [9] first detected the net current of 8–14 A in the interaction zone during the magnet-assisted CO_2 laser welding of an aluminum alloy, which they proposed to be the TEC, and later argued the possibility for a two-dimensional (2D) TEC distribution. Ambrosy et al. [12] also tested currents in the CO_2 laser welding process, although these were very weak currents in the Nd: YAG welding process. They thought that the main currents in the weld pool during CO_2 laser welding were not TEC but were caused by a laser-induced plasma jet. Lange et al. [13] analytically demonstrated and proved that the currents present during Nd:YAG laser conduction welding were indeed TECs. Furthermore, Lange et al. also predicted the 2D distributions of TEC, thereby

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confirming the original assumption suggested by Kern et al. However, the calculated directions between the two 2D distributions lay on opposite orientations. These research discoveries successfully found and explained some feathers of the TEC in the high-energy beam welding process. Unfortunately, the time-dependent evolutions of TECs are still not well understood.

In this paper, we propose a novel three-dimensional transient model of the thermoelectric phenomena in the fiber laser welding of austenite stainless steel and use it to investigate the characteristics of TECs. Our model includes the complex physical effects of thermal, electromagnetic, fluid and phase transformation dynamics occurring at the millimeter-scale laser ablated zone. The proposed model can simultaneously simulate characteristics of TECs as well as its keyhole and weld pool dynamics. The time-dependent evolutions, three-dimensional flow patterns of TECs, self-induced magnetic field, and Lorentz force during laser welding are predicted and analyzed. The magnitude and oscillation behaviors of TECs are theoretically studied and discussed. The predicted results are compared with the experimental and literature data.

2. Materials and methods

The present study used typical 304 stainless steels with a 3 mm plate thickness for the deep penetration laser welding experiments. The composition is shown in Table 1. A continuous wave (CW) fiber laser (IPG YLR-4000, maximum power: 4 kW) with a wavelength of 1.07 µm was used for bead-on-plate welding. The laser beam, which is delivered by a fiber system and focused on the specimen surface, has a spot radius around 0.2 mm at the focal position. The experimental setup for laser welding is shown in Fig. 1(a). The welding process parameters are shown in Table 2. Before welding the specimen was carefully cleaned with acetone to eliminate the possibility of the producing oil stains and oxide films. A shielding gas was not used during the welding process to maintain consistent simulation conditions. The weld was subsequently cut, ground, polished, and etched. The weld dimensions were then measured under an optical microscope (OM) to compare with the simulation results.

The complex dynamic behaviors of the thermal, electromagnetic, fluid, and phase transformations in the specimens were observed during laser welding [Fig. 1(b) and (c)]. The production principle of TECs is shown in Fig. 1(c) for the laser welding process. Different Seebeck coefficients between the solid and liquid metals [9] at different temperature gradients may have influenced the production of TECs. Maxwell electromagnetic theory may be equipped to solve for the induced TEC, magnetic field, Lorentz force and Joule heating. The boundary conditions (time-dependent L/S and L/V interfaces) and temperature gradients for the TECs can be calculated by solving the comprehensive computational fluid dynamics (CFD) model for laser welding. Currently, many researches have been made on the keyhole, weld pool and vapor plume behaviors and weld joints integrity during fiber laser welding [14–16]. Besides, the numerical simulation method has been an efficient way to be used to investigate the complex dynamic behaviors in laser welding, since proposed laser welding models display similar results to those derived from the experiments. There are many comprehensive laser welding CFD models, all of which could be used to reasonably predict the transient evolutions of the self-consistent keyhole, weld pool, and vapor plume [17–24]. Based on our previous well-tested CFD model of the keyhole and weld pool dynamics [18,25–30] and the Maxwell electromagnetic theory, the present study developed a novel three-dimensional theoretical model of the thermoelectric phenomena to solve the evolutions of TECs, self-induced magnetic field, and Lorentz force in the deep penetration laser welding process. Fiber laser welding was considered the main process for aforementioned model. The welding processes used in the simulations were the same as

Table 1
Chemical composition of 304 stainless steel.

Element	C	Si	Mn	P	S	Ni	Cr	Fe
%	0.07	0.46	0.78	0.032	0.06	8.10	18.32	Balance

Table 2
Process parameters for deep penetration fiber laser welding of 304 stainless steel.

Process No.	Laser power (kW)	Welding speed (m/min)	Beam radius (mm)
1	1.5	4.0	0.2
2	1.5	3.0	0.2
3	1.8	3.0	0.2

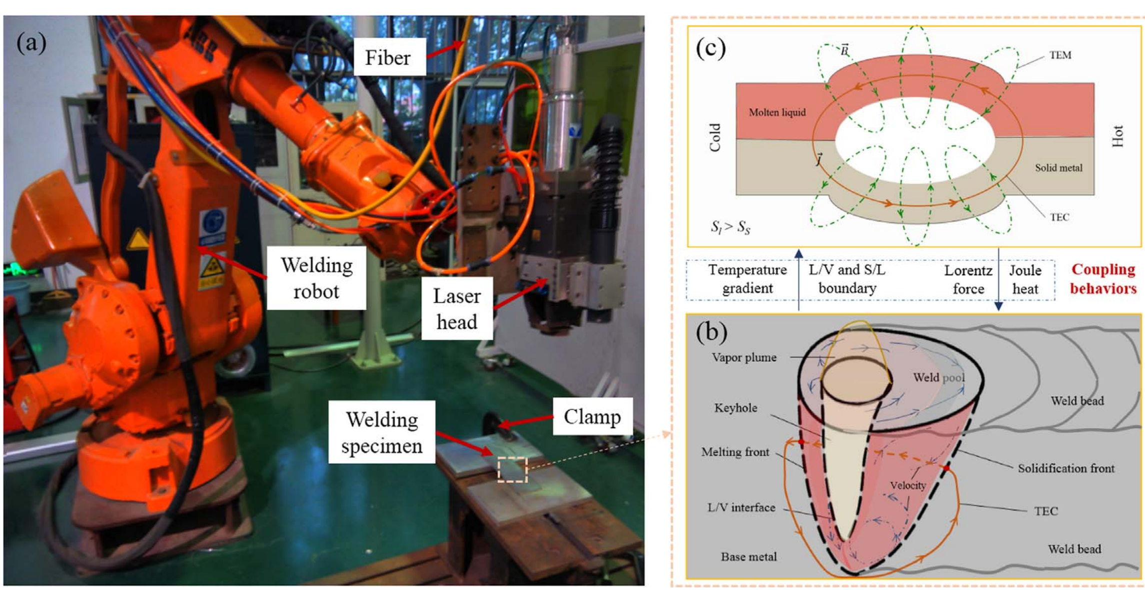

Fig. 1. Experimental setup and physical phenomena for fiber laser welding: (a) welding equipment; (b) dynamic behaviors of keyhole, weld pool and vapor plume in the keyhole; (c) the principle of the production of thermoelectric magnetic phenomena in weld pool; the coupling behaviors including the production of TEC and their effects on welding process is also shown between (b) and (c).