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Research Paper

Heat transfer and temperature distribution during high-frequency induction cladding of 45 steel plate

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HIGHLIGHTS

- A three-dimensional electromagnetic–thermal multifield coupling finite element model for HFIC was built.
- The heat used to melt the powder coating originates from the substrate–coating interface.
- Influence of different parameters on temperature distribution has been studied.
- The dissolution of WC particles corresponds with the temperature distribution.

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ABSTRACT

High-frequency induction cladding, a new surface-modification technology with high thermal efficiency and good formability, can be used to improve the surface mechanical properties of metal components. In this study, a three-dimensional electromagnetic–thermal multifield coupling model was developed to investigate heat transfer and temperature distribution in high-frequency induction cladding. Results showed that the heat used to melt the powder coating originates from the substrate–coating interface and that melting proceeds from the interior to the exterior of the coating. The effects of current density, current frequency, and air–gap spacing on temperature distribution were analyzed by using the effective size of the cladding area and the maximum temperature difference in the coating as reflections of temperature distribution. Microstructure analysis indicated that the dissolution of WC particles corresponds with temperature distribution, and a temperature field with low temperature difference in the coating is helpful for obtaining uniform microhardness distribution.

1. Introduction

Surface cladding methods, such as arc spraying, plasma spraying, and laser cladding, have been widely applied to repair and strengthen the surfaces of critical machinery components [1–3]. Nonetheless, the further applications of these methods are limited by some essential drawbacks, such as low energy conversion efficiency and high cracking susceptibility. High-frequency induction cladding (HFIC) is a relatively newly developed surface cladding method based on induction-heating technology. During HFIC, an alternative electric current is applied to produce an electromagnetic field, which induces eddy current in the workpiece. The heat released from the eddy current melts and bonds coatings with the substrate. HFIC has lower energy consumption and higher heating rates than other surface-modification methods and can be used to fabricate coatings with superior surface characteristics and excellent metallurgical bonding with substrates [4–6].

Numerous studies have been conducted to investigate the microstructure and mechanical behaviors of coatings prepared through HFIC. Wang et al. [7] prepared TiC/Ni composite coating from pre-alloyed Ni60, titanium, and graphite powders through HFIC. They obtained coatings reinforced with in-situ synthesized TiC particles and microhardness values of 1000–1100 HV. He et al. [8] investigated the mechanical properties of induction-melted Ni-based alloy coatings with different WC particle contents and found that increasing WC particle contents improves microhardness and wear resistance. Zhang [9] and Hu [10] obtained NiCrBSi and Fe-based alloy coatings through HFIC and intensively investigated the friction and wear behavior of the coatings.

HFIC is a complex thermal process that involves electric and magnetic fields. However, relatively few studies have examined temperature evolution in HFIC. Currently available investigations do not fully discuss the relationship between microstructure properties and the temperature field. Cen et al. [11] performed numerical simulations and experiments on the HFIC of boiler tubes and investigated the effects of

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current frequency and density on heating speed. Nevertheless, their simulations did not account for the nonlinearity of material properties. Given that HFIC was developed on the basis of induction heating, the temperature evolution of induction heating should also be investigated. Luozzo et al. [12] used the finite element method to analyze the temperature evolution of carbon steel tubes during induction heating and experimentally validated the simulated model. Han et al. [13] designed a profile coil to heat heavy-duty sprocket coils and numerically compared the differences in the heat transfer process between profile and normal circular coils. Song and Moon [14] considered the temperature dependency of material properties when simulating temperature distribution in induction heating for the forging of marine crankshafts.

Temperature distribution has important effects on the microstructure and mechanical properties of coatings processed through HFIC. Controlling the distribution of the temperature field is helpful in improving cladding efficiency and quality. In addition, the metallurgical bonding between two materials with different properties is affected by the process of heat transfer. Therefore, the objective of this study was to build a three-dimensional electromagnetic–thermal multifield coupling model and investigate the characteristics of heat transfer and temperature distribution in the process of HFIC. The influence of key process parameters on temperature distribution was investigated to provide the theoretical basis for temperature field control. A cladding experiment was conducted to verify the finite element model and evaluate the effect of temperature distribution on the microstructure and microhardness of coatings.

2. Description of the mathematical model

2.1. Description of the electromagnetic field model

The eddy current generated in the workpiece during induction heating is dependent on the alternative magnetic field. The governing equations of electromagnetic induction heating are Maxwell's equations, which can be described as follows:

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t} \tag{1}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{2}$$

$$\nabla \cdot \boldsymbol{B} = 0 \tag{3}$$

$$\nabla \cdot \boldsymbol{D} = \rho \tag{4}$$

where $\boldsymbol{H}$ is the magnetic field intensity, $\boldsymbol{J}$ is the electric current density associated with free charges, $\boldsymbol{D}$ is the electric displacement vector, $\boldsymbol{E}$ is the electric field intensity, $\boldsymbol{B}$ is the magnetic flux density, and ρ is the electric charge density. In HFIC, displacement current density $\partial \boldsymbol{D}/\partial t$ is not the main contributor of joule heat that melts the alloy powders, and induced conduction current $\boldsymbol{J}$ is considerably greater than the displacement current density $\partial \boldsymbol{D}/\partial t$; therefore, $\partial \boldsymbol{D}/\partial t$ in the equations should be negligible [15].

Moreover, the physical parameters $\boldsymbol{H}$, $\boldsymbol{J}$, $\boldsymbol{B}$, and $\boldsymbol{E}$ obey the following auxiliary equations:

$$\boldsymbol{B} = \mu \boldsymbol{H} \tag{5}$$

$$\boldsymbol{J} = \sigma \boldsymbol{E} \tag{6}$$

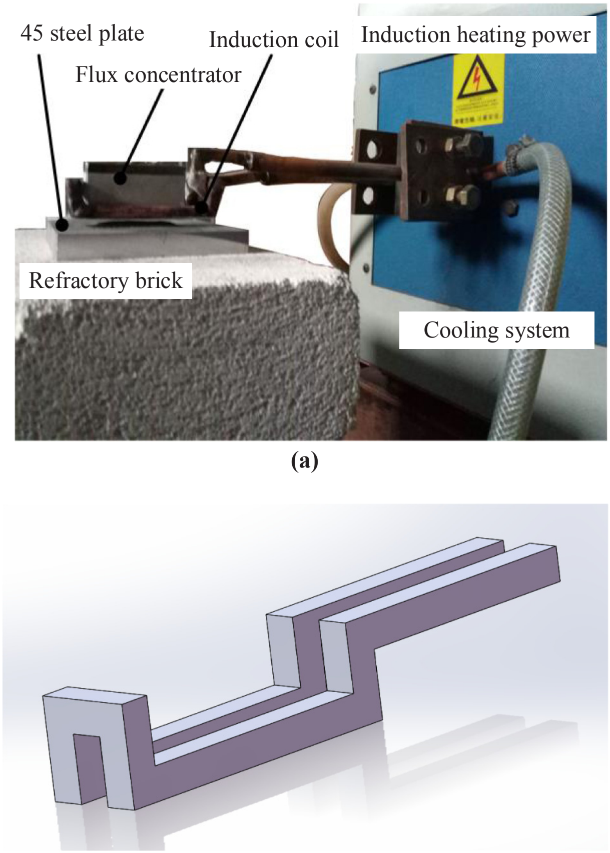
where μ is magnetic permeability, and σ is electrical conductivity.

The magnetic vector potential $\boldsymbol{A}$ is introduced on the basis of the Helmholtz theorem, and the following equation is obtained:

$$\boldsymbol{B} = \nabla \times \boldsymbol{A} \tag{7}$$

Thus, the electric field intensity $\boldsymbol{E}$ can be described as follows from Eqs. (2) and (7):

$$\nabla \times \left[\boldsymbol{E} + \frac{\partial \boldsymbol{A}}{\partial t} \right] = 0 \tag{8}$$



(a)

(b)

Fig. 1. Experimental device and induction coil applied in high-frequency induction cladding. (a) Experimental device. (b) Induction coil.

The electric scalar potential φ is introduced because $\nabla \times (\nabla \varphi) = 0$ meets Helmholtz theorem. Eq. (8) can be further described as follows:

$$\boldsymbol{E} = -\frac{\partial \boldsymbol{A}}{\partial t} - \nabla \varphi \tag{9}$$

In accordance with Eqs. (1), (5), and (6), and (7), the governing equation in the eddy current domain is derived as:

$$\nabla \times \frac{1}{\mu} \nabla \times \boldsymbol{A} + \sigma \frac{\partial \boldsymbol{A}}{\partial t} + \sigma \nabla \varphi = 0 \tag{10}$$

The boundary conditions of continuity between regions with different properties are as follows:

$$\boldsymbol{n} \times (\boldsymbol{H}_1 - \boldsymbol{H}_2) = 0 \tag{11}$$

$$\boldsymbol{n} \cdot (\boldsymbol{B}_1 - \boldsymbol{B}_2) = 0 \tag{12}$$

Moreover, in the outermost boundary of the model, the magnetic vector potential $\boldsymbol{A}$ is 0.

2.2. Description of the temperature field model

Induction heating is a process that occurs with drastic temperature increase, and an extreme temperature gradient will exist in the surface layer of the workpiece because of the skin effect. Thus, this nonlinear transient heat transfer process can be expressed by the Fourier equation as follows:

$$k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + Q = \rho c \frac{\partial T}{\partial t} \tag{13}$$

where k is the thermal conductivity coefficient, Q is internal heat source intensity due to the eddy current, c is specific heat capacity, and ρ is