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Design and research on the spot inductor for obtaining local high temperature rapidly

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ABSTRACT

In order to improve heating performance of spot inductor and realize the hardening or cladding of complicated curve surface workpiece, two novel spot inductors were designed and their models coupled electromagnetic and temperature fields were built in ANSYS. Experimental validation was also carried out for these two inductors. The experimental temperature result was in good agreement with the simulation on workpiece surface. It indicated that the heating performance (including heating temperature and rate) of vertically aligned spot inductor was the highest among those spot inductors and its temperature value reached to 1660 °C in case of heating at 20s with the input power of 50 kW. With the same input power value, the heating performance of horizontally aligned spot inductor was better than that of the ordinary spot inductor. Moreover, the final temperature uniformity of horizontally aligned spot inductor was better than that of vertically aligned spot inductor, whose values are about 92.5% and 89.5% respectively. The local high temperature generated by vertically aligned spot inductor would melt many kinds of metal powder, and can be used for cladding and hardening of complicated curve surface workpiece.

1. Introduction

Induction heating has been widely applied in the industry due to the fast heating rate and high efficiency [1]. In order to strengthen the complicated shape workpieces, spot induction heating as a novel process was presented by some researchers in recent years [2]. A small size inductor was designed and assembled to a five-axis cooperating CNC (computer numerical control) machine tool, which can realize the heating of a small region on the complicated surface profile workpiece [3]. The coil of spot inductors is usually designed in U shape due to the limitation of workpiece shape and its structure. When current flows in the coil, eddy current was induced on the surface layer of workpiece mainly by the bottom parts of U shape coil. On one hand, the effectiveness of power supply is relatively low because only a short part of copper pipe can be used to induce eddy current in workpiece. On the other hand, once the temperature of workpiece reached the Curie point [4], the heating efficiency of inductor would decrease with the decline of the relative permeability. Therefore, the heating performance of spot inductor is limited, which is usually below 1000 °C [2, 5]. This has now become the key factor that limits spot induction heating applied at induction cladding, surface remelting for complicated curve surface.

In order to improve the heating performance of inductor, many researchers did a lot of related researches. Shih et al. [6] proposed a multizone induction heating approach that entails dividing a target surface into several zones and then applying numerous sets of short inductive coils to the individual regional zones for heating. Compared with single-zone induction heating, the multiple- zone induction heating of a largely curved mold surface enhanced the heating rate and uniformity performance. Nian et al. [7] used ferrite materials to separate the conflicting magnetic fields caused by the repulsive proximity effect. Several coils are investigated in his study, appropriate placement of ferrite materials on these induction coils successfully eliminated the proximity effect, increased the heating rate, and improved temperature uniformity. In another work of Nian [8], the effects of several parameters on the heating rate and temperature uniformity of induction heating on a mold surface by using a single-layered coil were analyzed. Both simulation and experimental results indicated that the thickness of a heated target plays a crucial role in affecting the heating rate. Moreover, the position of the induction coil exerts the most notable effect on heating uniformity. Gao et al. [5] carried out simulation and experiment of induction heating process with different magnetizer geometries, with the aim of investigating the magnetizer geometry on heating rate and temperature uniformity of AISI 1045 steel workpiece. Some laws how the length and width of magnetizer affect induction

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heating were found, and the best shape of magnetizer was obtained in his research models. In order to control induction preheating of the joint sides up to the desired depth, Ikram et al. [9] designed a horizontal coil and a vertical coil, and compared heating performance of them. It was found that a horizontal coil with a magnetizer performed well in terms of the heating rate and temperature difference across the joint sides. And a higher heating rate was found on the workpiece with the coil having a magnetizer compared to without a magnetizer. Although lots of related researches have considered different factors which may affect the heating performance of inductor, the study on the design of inductor used for fast heating was really rare.

In this paper, in order to expand the application fields of spot induction heating process, new spot inductors were designed and its finite element model of induction heating was established by ANSYS. In the paper, study was conducted on the heating rate as well as the temperature uniformity on workpiece surface. In addition, the experiments were carried out to validate the built model.

2. Mathematical model

2.1. Design of new spot inductor

Geometric model of spot induction heating is shown in Fig. 1. The whole geometric model includes inductor, workpiece (the blue part) and air (the yellow part). The inductor includes coil (the red part) and magnetizer (the black part). As high-frequency alternating current flows in the coil, a great deal of eddy current is induced in the workpiece surface layer which leads to the temperature of surface layer increasing drastically.

The geometric model of ordinary spot inductor is shown in Fig. 1. In order to improve the heating performance of spot inductor, two modified spot inductors were designed with the method of increasing the aligned turns of coil in horizontal or vertical direction; Besides, a U shape magnetizer was designed, which was installed on the coil, and the undersurface of the U shape magnetizer is parallel to that of the inductor, or that it matches with the surface of the workpiece. The geometric model of these two inductors was shown in Fig. 2.

2.2. Eddy current field

During the process of induction heating, the model can be divided into eddy current part and no eddy current part. Eddy current part is the area with eddy current in workpiece, while no eddy current part includes the inductor, air and the rest part of workpiece. For eddy current part, the eddy current field model can be described by Maxwell eqs. [10]:

$$culH = J + \frac{\partial D}{\partial t} \tag{1}$$

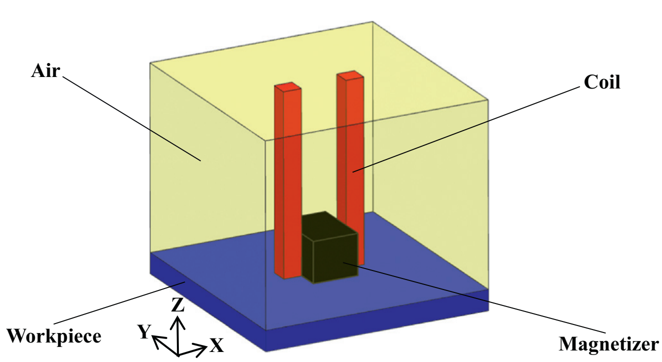

Fig. 1. Geometric model of spot induction heating.

$$culE = -\frac{\partial B}{\partial t} \tag{2}$$

$$divD = \rho_\varepsilon \tag{3}$$

$$divB = 0 \tag{4}$$

where H denotes the magnetic field intensity, J is the magnetic flux density, D is the electric flux density, E is the electric field intensity, B is the magnetic flux density, ρ_ε is the charge density, t is the time.

The frequency of electromagnetic field is low during the induction heating process, the field source changed slowly over time; therefore, it can be seen as the quasi-stationary electromagnetic field. The displacement current in quasi-stationary electromagnetic field is very small, and the change of magnetic field caused by electric field can be ignored [11]. Hence, the simplified Maxwell equations are concluded as follows:

$$curlH = J \tag{5}$$

$$curlE = -\frac{\partial B}{\partial t} \tag{6}$$

$$divB = 0 \tag{7}$$

The electromagnetic field can be expressed as follows:

$$B = \mu H \tag{8}$$

$$J = \sigma E \tag{9}$$

where μ is the magnetic permeability, and σ is the conductivity. Because solving the two Maxwell equations of (8)~(9) directly is very difficult, the magnetic vector potential A and electric scalar potential φ are introduced, with the two parameters defined as follows:

$$B = curlA \tag{10}$$

$$E = -\frac{\partial A}{\partial t} - \nabla\phi \tag{11}$$

Combined with formulas (10)~(11), the formulas (5)~(7) can be calculated. According to the uniqueness of vector field, the divergence is uncertain although the curl of magnetic vector potential A has been confirmed. Therefore, Coulomb gauge in the classical electromagnetic field is used to define the divergence of magnetic vector potential A in this paper:

$$divA = 0 \tag{12}$$

$$div(\nabla\phi) = 0 \tag{13}$$

The eddy current field equations can be obtained as follows [12]:

$$J = \sigma\frac{\partial A}{\partial t} + \frac{1}{\mu}curl[curlA] \tag{14}$$

$$A = BSL \tag{15}$$

where S is the area of plane that perpendicular to the direction of magnetic field, and L is the length of Magnetic Circuit. According to formulas (14)~(15) and Fig. 3, it can be concluded that the eddy current values on the surface layer of workpiece induced by horizontally aligned spot inductor and vertically aligned spot inductor are greater than the eddy current values induced by ordinary spot inductor, which thus indicates better heating performance.

2.3. Temperature field

During the process of induction heating, temperature of workpiece changes dramatically, and there is a large temperature gradient along the thickness direction. Therefore, the nonlinear 3D differential equation is used to describe the changeable temperature field T(x, y, z); besides, the transient thermal analysis model is chosen as the thermal analysis model of the workpiece, and the Fourier equations is used to describe the temperature change laws [13]: