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Effect of magnetizer geometry on the spot induction heating process

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ABSTRACT

Simulated and experimental analysis of spot induction heating process with different magnetizer geometries were carried out with the aim of investigating the magnetizer geometry on heating rate and temperature uniformity of AISI 1045 steel workpiece. The simulated temperature field was in good agreement with experimental temperature field on workpiece surface. According to the calculated results, the highest heating rate could be obtained when magnetizer width was 10 mm, length was 20 mm and height was greater than the critical saturation value ($h_{saturation}$). The uniformity of temperature distribution could be improved by increasing the magnetizer width but became worse by increasing the magnetizer length. Additionally, the variation of input current had no effect on the appearance position of the highest heating rate under different widths.

1. Introduction

Induction heating process, whose aim is to enforce some specific properties for manufactured parts, has become quite popular in industry in the last two decades due to the following reasons: fast heating rate, good reproducibility and low energy consumption (Davies, 1990). Inductor design is one of the most important aspects of an induction heating system. A well-designed inductor can produce a proper heating pattern and improve the efficiency of the induction heating process. A small size inductor used in the spot induction hardening (SIH) method, has been presented in the previous work (Gao et al., 2014) with the aim of hardening complicated shape workpiece. In SIH process, the inductor consisted of a single-turn copper coil and magnetizer (also called electromagnetic flux concentrator). Due to the small size of coil and the beneficial effect of magnetizer on strengthening heating efficiency, the inductor was assembled to a five-axis cooperating CNC (Computer numerical control) machine tools, which was suitable for surface hardening on complicated shape workpieces. In order to obtain the further improvement on heating efficiency and temperature uniformity during the heating process, magnetizer geometry should be considered as an important factor.

Some researches have considered the effect of inductor coil and workpiece geometries in induction heating process and done some optimization analysis. Bui and Hwang (2015) modeled a coil coupled with magnetic flux concentrators for barrel induction heating in an injection molding machine. Different pitches of magnetic flux concentrators were applied with the aim of studying the uniform heating capability of induction heating system with heating coil coupled with magnetic flux concentrators via commercial software, ANSYS. Simulated results showed that changing diameters of a barrel or varying operation frequency of induction power supply had no effect on uniform temperature distribution on the inside surface of the barrel. Nian (2014a) proposed a novel magnetic shielding method to enhance the induction heating efficiency for injection mold surface. In the novel magnetic shielding induction heating method developed in their study, heating efficiency and temperature uniformity were enhanced by using ferrite materials to separate the conflicting magnetic fields caused by the repulsive proximity effect. Finally, appropriate placement of ferrite materials on these induction coils successfully eliminated the proximity effect, increased the heating rate, and improved temperature uniformity. Another work of Nian (2014b) investigated the key parameters and optimal design of a single-layered induction coil for external rapid mold surface heating. The effects of the thickness of a heated target, pitch of coil turns, heating distance, position of the induction coil, working frequency, and waiting time on the heating rate and temperature uniformity of induction heating on a mold surface by using a single-layered coil were analyzed. Both simulated and experimental results indicated that the workpiece thickness played a crucial role in affecting the heating rate. Specifically, a more rapid heat dissipation occurred in a thicker workpiece after induction heating. Moreover, the position of the induction coil exerted the most notable effect on temperature uni-

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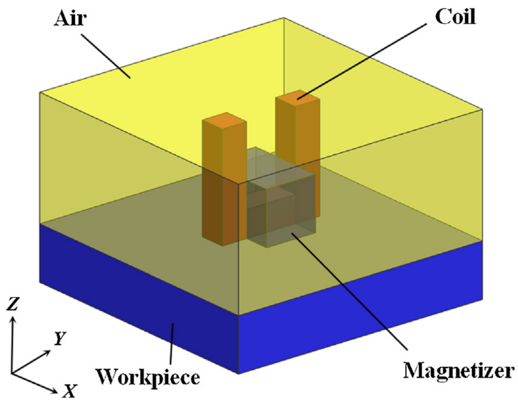

Fig. 1. Physical model of 3D spot induction heating.

formity. Tavakoli et al. (2009) considered the effect of different shapes and orientations of coil in the Czochralski crystal growth system and obtained the electromagnetic field and volumetric heat generation results by using finite element method. The calculated results showed cross section shape, geometry and position of the coil as well as after heater had an important effect on the heating process. The subsequent work of Tavakoli et al. (2011) analyzed the effect of workpiece height on the induction heating process. A set of 2D steady state finite element numerical simulations of electromagnetic fields, eddy currents distribution and induction heating pattern was performed for different heights of a metal workpiece. Comparison between the calculation results showed the distance between workpiece body and induction coil had a marked effect on the electromagnetic field distribution, eddy currents profile, heating structure and coil efficiency in the system. Naar and Bay (2013) introduced a new approach for designing and optimizing induction heating process. They focused on the optimization of the Heat Affected Zone in the induction heating process. Zero- and first-order algorithms have been tested and coupled with 2D and 3D multi-physics finite element models for solving induction heat treatment problems. Although there were a lot of works considering different factors which may affect the heating rate and temperature uniformity in induction heating process, such as pitch of magnetizer, thickness of workpiece, pitch of coil turns, position of coil and working frequency, the works dealing with the effect of magnetizer geometry were relatively rare.

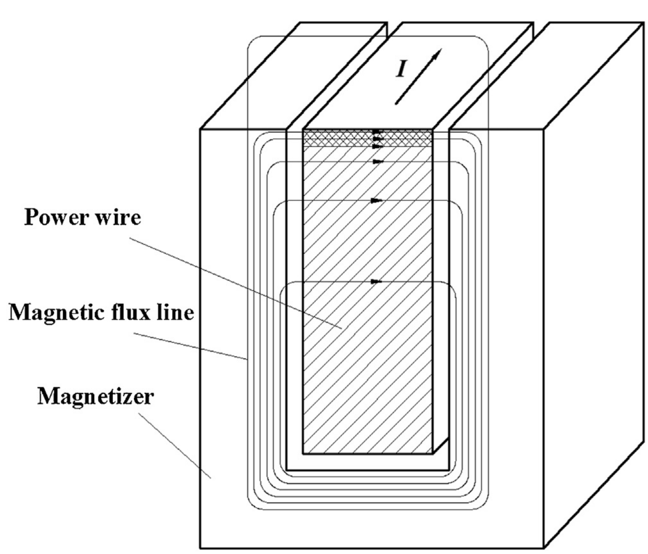

Fig. 2. Schematic diagram of the effect of magnetizer on the magnetic flux field distribution around the electric conductor.

Table 1
Physical dimensions.

Item	Parameter	Units
Workpiece material	AISI 1045 steel	
Workpiece dimension	100 (*L*) × 100 (*W*) × 20 (*H*)	mm
Magnetizer material	Ferrite	
Initial and relative permeability of magnetizer	1500 and 1.19×10^8	
Coil material	Copper	
Coil dimension	10 × 10 (cross section)	mm
Frequency	30	kHz
Maximum power	50	kW
Total heating time	7	s
Initial and environmental temperature	20	°C
Distance between coil and workpiece	2	mm

In this paper, a FE method using a commercial package, ANSYS, was presented for analyzing the effect of magnetizer geometry on spot induction heating process. Electromagnetic and temperature field distributions with different magnetizer geometries were investigated. The main purpose of this work was to optimize magnetizer geometry with aim of obtaining high heating rate and temperature uniformity in spot induction heating process.

2. Mathematical model

The physical model of spot induction heating is depicted in Fig. 1. The whole model consists of coil (the red part), magnetizer (the black part), workpiece (the blue part) and air (the yellow 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.

2.1. Eddy current field

During the induction heating process, the eddy current field model can be described by Maxwell equations:

Magnetic flux equation

$$\nabla \cdot \boldsymbol{B} = 0 \tag{1}$$

Maxwell–Gauss equation

$$\nabla \cdot \boldsymbol{E} = 0 \tag{2}$$

Maxwell–Faraday equation

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

Maxwell–Ampere equation

$$\nabla \cdot \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t} \tag{4}$$

where $\boldsymbol{H}$ denotes the magnetic field intensity, $\boldsymbol{B}$ is the magnetic flux density (Pechstein and Jüttler, 2006), $\boldsymbol{E}$ is the electric field intensity, $\boldsymbol{D}$ is the electric flux density and $\boldsymbol{J}$ is the electric current density. Because of non-linearity of the processed workpiece the distribution of electromagnetic field is generally described by the

Table 2
Geometric parameters of magnetizer used in the simulation.

Number	Length (mm)	Width (mm)	Height (mm)
1–5	4, 8, 12, 16, 20	10	10
6–13	20	1, 3, 5, 8, 9, 10, 11, 15	10
14–18	20	10	1, 3, 5, 7, 9