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Comparison between single- and multiple-zone induction heating of largely curved mold surfaces☆

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ABSTRACT

This study applied three-dimensional steady-state finite-element numerical simulations of electromagnetic fields and temperature distributions to evaluate the effects of various coil geometries, regional depositions, and magnetic shielding materials on the induction heating of a curved mold plate surface used for fabricating automotive spoilers. Conventionally, the induction heating of large mold surfaces by using a set of long inductive coils entails employing a costly, high-power induction heating device. This study proposes a multizone induction heating approach that entails dividing a target surface into several zones and then applying numerous sets of short inductive coils that require only low-power induction heating devices to the individual regional zones for heating. In this approach, the coil design is relatively simple for efficiently heating these small-area zones. The simulation results are described as follows: (1) the geometry of the inductive coils with respect to the processed workpiece demonstrated a considerable effect on the electromagnetic field distribution and the heating efficiency of the system. (2) Magnetic shielding materials facilitated eliminating the proximity effect, which produces a nonuniform heating pattern along the workpiece wall. (3) Compared with single-zone induction heating, the multiple-zone induction heating of a largely curved mold surface enhanced the heating rate and uniformity performance.

1. Introduction

Variothermal processes in injection molding are effective in completely filling mold cavities with molten plastics, which prevents the occurrence of surface faults, such as short shots, imbalanced filling, sink marks, fiber streaks, weld lines, and warpage, and enables the production of microstructured parts [1]. Conventional variothermal processes that involve heating with water or oil have the disadvantages of a long cycle time and low productivity because of a low heat-flux density. Electromagnetic induction heating facilitates achieving a fast heating rate because it demonstrates an excellent heat-flux density and heats only the mold surface rather than entire mold blocks, enabling the mold to be cooled rapidly; therefore, this approach is highly suitable for rapidly heating mold surfaces in dynamic mold temperature control systems [2–4].

Effective induction heating relies on the design and manufacture of the employed inductive coils. Heating rates and uniformity performance may vary among inductive coils. Previous studies on induction heating have typically addressed three topics: (1) the effect of coil turns on induction heating [5–7]; (2) the effect of process parameters, such as the working frequency heating distance and the target thickness, on induction heating [8,9]; and (3) the effect of the target geometry on heating performance and sensitivity analysis reports on the location of inductive coils relative to the processed workpiece [10,11]. However, few studies have examined the effect of locally heating largely curved mold surfaces by using multiple inductive coils. In particular, most coils designed for heating large mold surfaces comprise a set of long inductive coils requiring costly high-power heating devices. This thus necessitates the evaluation of induction coils for large mold surfaces with curved shapes because they can affect the temperature distribution during the heating process and the level of energy consumption. Therefore, the objective of the present study was to achieve efficient and uniform heating by dividing the target surface into several zones equipped with only low-power induction heating devices and then heating the zones with short inductive coils. In addition, the effects of using magnetic shielding materials on induction performance were examined. Commercial simulation software COMSOL Multiphysics was used to analyze the magnetic and thermal properties of the material.

2. Induction heating principle

The principle of induction heating is to place a processed magnetic or nonmagnetic conductive workpiece in a high-frequency electromagnetic field produced by an inductive coil, which is connected to a high-frequency generator. The time-varying electromagnetic field induces the excitation of eddy currents I_c at various depths in the workpiece

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Table 1
Magnetic properties of ferrite materials.

Properties	Initial permeability, μ_i	Relative permeability, μ_r	Resistivity, Ω-m
Ni–Zn ferrite	1500	1.19E8	1E7
Mn–Zn ferrite	2300	1.83E8	8

lying within the field of the inductive coil. The resistance of workpiece R and the induced eddy current generates a heating power equal to I_c^2R, thereby heating the target.

Induction heating exploits three major effects: the skin effect, proximity effect, and ring effect. The skin effect is induced by the frequency and the coupling distance, whereby a higher frequency facilitates the rapid heating of a specific workpiece but limits the penetration depth of the electromagnetic field. The effect relies on the electromagnetic fields produced by induced currents. Reducing the coupling distance strengthens the increase in local temperatures; however, this can lead to highly inhomogeneous heating. The proximity effect is induced by interference from nearby conducting elements that disrupt the electromagnetic field. Higher frequencies or smaller gaps between processed workpieces and inductive coils correspond to a stronger proximity effect. The generated eddy current increases the flux approaching the mold face and causes the current to penetrate at a shallow depth, consequently increasing the degree of heating. By contrast, longer distances reduce the flux, thus weakening the heating effect; the consequent effect on the skin influences the distribution of the eddy current. The ring effect is caused by the sudden interaction of magnetic fields generated by the current flow in two adjacent charged conductors or coils, thereby affecting the change of flux. In particular, the concentration of magnetic field lines in a circular coil causes the magnetic field and heating distribution to become inhomogeneous [7].

The major effects of an induction setup originate from the magnitude of the induced currents, the resistance of the workpiece to the flow of the currents, the length of time the workpiece is exposed to the field, the geometry and orientation of the workpiece and the inductive coil, and the use of magnetic flux concentrators or magnetic shielding materials. The current study emphasized on the effects of coil geometry and magnetic shielding materials on induction heating.

2.1. Coil geometry

Coils influence electromagnetic coupling and frequency because part of the oscillating electromagnetic circuit affects the penetration depth. Commonly used heating coils can be categorized into single-turn and multiturn types [7,12]. Single-turn heating coils are suitable for small heating areas, whereas multiturn heating coils provide higher power and require less time for heating. Ensuring the compatibility of various coils in a particular setup is challenging because the dissimilar impedances corresponding to each coil type imply that the setup is nonuniform. However, the coil geometry must be modified and improved, and the processing parameters must be adapted to broaden the application of induction heating in the injection molding industry.

2.2. Magnetic concentrating and magnetic shielding methods

In induction heating, the proximity effect changes the current distribution when the processed workpiece is close to the inductive coil. The current is distributed along the coil surface, which causes a loose distribution of eddy currents on the processed workpiece. Therefore, the surface heating effect is insufficient. The authors of the current study have proposed a novel magnetic shielding induction heating method for solving the repulsive proximity problem in their previous studies [11,13,14]. Ferrite materials can be used to separate conflicting magnetic fields, which are induced by two adjacent coils with inverse current directions, to remove the effects of repulsive proximity and subsequently enhance the heating efficiency and temperature uniformity.

Magnetic concentrators exhibiting material properties resembling those of transformer coils (i.e., a high conductivity and low resistance) are commonly used to enforce the coil current and eddy current distribution, which then enhances its heating rate; however, using such concentrators is associated with limitations [13]. For two adjacent opposite-current coils, introducing a magnetic concentrator can separate the magnetic fluxes between the concentrators and concentrate the magnetic flux below the coils, but this cannot prevent the proximity effect that occurs under the coils. Therefore, the center of the workpiece demonstrates a lower heating efficiency and a lower temperature. In contrast to the magnetic concentrator method, the magnetic shielding method entails completely separating the magnetic flux fields from different coils and driving the magnetic flux uniformly throughout the workpiece surface. In the magnetic shielding induction heating method, ferrite materials are used to separate conflicting magnetic fields. Normal ferrite materials can be typically categorized into two groups: Mn–Zn and Ni–Zn ferrites. Both ferrite materials are widely used in transformer coils and are easily magnetized and demagnetized. Table 1 shows the magnetic properties of Mn–Zn and Ni–Zn ferrites. In this study, a Ni–Zn ferrite was used for the experiment because it exhibits a considerably higher resistivity (1E7 Ω-m) than that of a Mn–Zn ferrite (8 Ω-m). The higher resistivity is advantageous to prevent the ferrite from being heated during the induction heating process, therefore leading to less energy consumption.

3. Multiphysical simulation of induction heating

Simulating the electromagnetic induction of a workpiece is a multiphysics problem involving at least the theories of electromagnetism and heat transfer [15,16]. To design an optimal inductive coil for

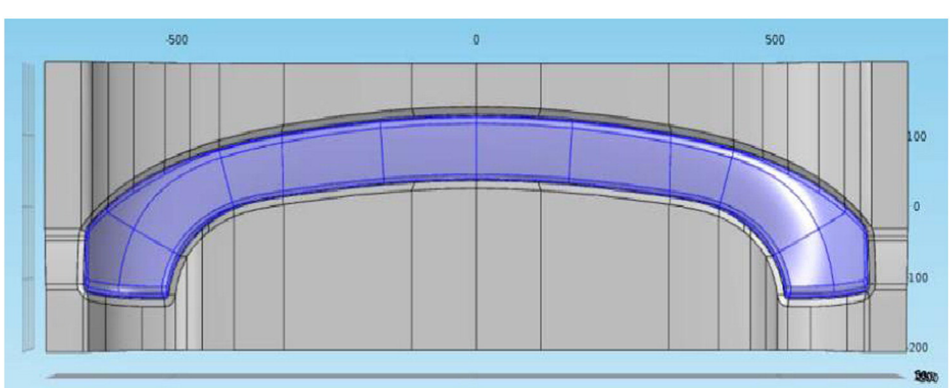

Fig. 1. Geometric dimensions (1400 × 400 × 200 mm) of a female mold plate used for fabricating automotive spoilers (the blue area represents the surface to be heated). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)