Numerical study on temperature distribution of the hot-plate under induction heating

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Abstract. In this paper, a novel method based on electromagnetic heating theory is introduced to achieve a stable and uniform temperature distribution on the target surface of the hot-plate. The heat process of hot-plate is divided into two stages. At first, the thin layer of S45C was coated on the surface of the hot-plate by thermal spraying. Due to skin effect, coated S45C layer can be considered as heat source in terms of the law of electromagnetic heating. Secondly, the hot-plate made of pure aluminium with a high thermal conductivity can be employed to reduce the temperature difference. Finally, the target surface temperature of the hot-plate is stabilized at specific temperature by changing the holding current.

1. Introduction

With the continuous development of society, rubber products are more and more closely connected with all aspects of people's life, and the rubber industry has gradually become an important sector in the national economy. Rubber vulcanization is the last and most important process in the production of rubber products. The control of vulcanization process is directly related to the product quality and production efficiency [1].

The temperature, pressure and time are the three basic elements of vulcanization, and accurate control of these three elements is a key to determine the product quality. The aging resistance and abrasion resistance of rubber products are closely related to vulcanization temperature. If the surface temperature difference of the hot-plate is non-uniform, the phenomenon of over-sulfur or under-sulfur will occur [2]. Plate vulcanization machine is the main vulcanizing equipment for rubber products, so the temperature difference on the surface of the hot-plate is the main performance index to evaluate plate vulcanization machine. According to industry standard, the temperature of the working surface must be controlled in 3°C for the high quality products.

Electromagnetic heating is applied to the hot plate field of vulcanizer due to its fast heating speed and high efficiency. In past studies, researchers employed various methods to control the temperature with less heat fluctuations. First of all, the coil shape plays an important role in electromagnetic heating [3]. However, it is difficult to control the temperature difference within the industry standard simply by optimizing the coil [4]. Besides, many studies revealed that the temperature was increased obviously with the enhancement of the current and frequency. Unfortunately, the temperature difference of hot-plate was enlarged remarkably [5].
So far, there is no systematic design method followed completely electromagnetic heating theory, so that the surface temperature of the hot-plate can quickly reach at allowable range to meet the industrial standard. In this study, a new type of the hot-plate and analytical procedure were proposed numerically to achieve stable and uniform temperature distribution on the target surface of the hot-plate in term of the theory of electromagnetic heating.

2. Theoretical analysis of induction heating

Figure 1 shows the schematic view of the installation of the hot-plate. The hot-plate is fixed on the lifting plate. Due to the presence of asbestos layer, the heat of the hot-plate is effectively prevented from being transmitted to the lifting plate.

![Figure 1. Schematic view of the hot-plate installation.](image)

In addition, the magnetic insulating material sufficiently isolates the influence of the electromagnetic effect on the lifting plate. In the physical model, the hot-plate involves an electromagnetic and temperature field, which can be described as follows:

2.1. Electromagnetic field equations

According to Maxwell's equation, when the coil is connected to an alternating current, an alternating magnetic field is generated around the coil. In an alternating magnetic field, the cutting of magnetic lines of force on the metal surface creates eddy currents. In the induction heating process, the eddy current field distribution in electromagnetic induction heating process can be obtained [6]:

\[
(j \omega \sigma - \omega^2 \varepsilon_0 \varepsilon_r) \nabla \times (\mu_0^{-1} \mu_r^{-1} \nabla) = J \varepsilon
\]

where \(\sigma\) is the electrical conductivity, \(\omega\) is the angular frequency and \(\nabla\) is the magnetic potential energy vector. \(\varepsilon_0\), \(\mu_0\), \(\varepsilon_r\) and \(\mu_r\) stand for the permittivity, permeability of free space, the relative permeability and permeability, respectively.

During induction heating, the induced current is concentrated in the penetration depth of thickness \(\delta\) due to skin effect as follow [7]:

\[
\delta = \sqrt{\frac{\rho}{f \mu_1}}
\]

where \(\delta\), \(f\) and \(\rho_1\) are the penetration depth (m), the alternating current frequency (Hz) and electrical resistivity, respectively. The heat is first generated in the \(\delta\), and the aluminium hot-plate is heated by heat conduction.

When the magnetically insulated boundary exists in a magnetic field, the boundary conditions can be summarized as:

\[
\vec{n} \times \vec{A} = 0
\]
where $n$ represents the unit normal vector. For the magnetic potential energy $A$ parallel to boundary is equal to zero $A = 0$ and $\frac{\partial A}{\partial n} = 0$, if $A$ is normal to boundary condition. In particular, $A$ is equal to zero for the infinite domain.

2.2. Temperature field governing equation

The purpose of solving the electromagnetic field and the eddy current field is to calculate the temperature field by using the Joule heat generated as the internal heat source. In addition, assuming that the material properties of the heated specimen are isotropic, the temperature governing equation is as follows [8]:

$$
\rho \cdot c(T) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left[ \lambda(T) \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial y} \left[ \lambda(T) \frac{\partial T}{\partial y} \right] + \frac{\partial}{\partial z} \left[ \lambda(T) \frac{\partial T}{\partial z} \right] + q_v
$$

(4)

where $\rho$ stands for material density. $c(T)$ and $\lambda(T)$ represent the temperature-dependent specific heat capacity and thermal conductivity, which associated with temperature. $q_v$ is the intensity of heat source in induced eddy current. The boundary condition equation at the interface between the coil and the air is given as [7]:

$$-n_{air} \cdot (-\lambda_{air} \nabla T_{air}) - n_{coil} \cdot (-\lambda_{coil} \nabla T_{coil}) = 0$$

(5)

The boundary condition for the insulation layer is $q = 0$. For the infinite domain, the temperature $T = T_0$ is set, where $T_0$ is the initial temperature of 25°C.

3. Multiphysical simulation of induction heating

In practical industrial production, the original hot-plate made of S45C steel is widely used. For comparison, the original size of the hot-plate was employed as well in this paper. Figure 2 shows a physical model of induction heating of composite hot-plate. The size of the hot-plate is 500 mm in length, 500 mm in width and 78 mm in height. Since the eddy current distribution is approximately the same as the coil shape [9], the shape of the coated area on the composite hot-plate is similar to the coil shape as shown in Figure 2(a). The spray size was set to $L = 46$ mm in the simulation, as shown in Figure 2(b).

To reduce the temperature difference of the hot-plate, the aluminum alloy with a higher thermal conductivity was employed to make hot-plate. Since S45C steel has higher electrical resistivity and higher induction heating efficiency, S45C steel is still used to coat a specific area on top surface of the hot-plate using a conventional thermal spray process.

The area away from green line outward is a contact area between the hot-plate and the lift plate, as shown in Figure 2(b). To reduce heat loss, the asbestos layer was attached around the four-side of the hot-plate as well, as shown in Figure 2(a). To protect the aluminum material from damage, the S45C steel plate with a thickness of 2mm is laid on the top of composite hot-plate in direct contact with the mold.

The temperature-dependent material thermal and electromagnetic properties of the hot-plate applied in the simulation are shown in Table 1.

Due to the advantages of COMSOL Multiphysics Version 5.3a in multiphysics coupling, the COMSOL Multiphysics is employed to study temperature distribution on the surface of the hot-plate under induction heating. The mesh system of the model is shown in Figure 3. Meshing the hot-plate with a prismatic mesh in COMSOL can significantly reduce the number of meshes. Due to the effect
of skin effect, the mesh depth is refined within the skin depth, and the coil and water are divided by a sweeping grid. The tetrahedral mesh is employed to approximate complex physical region of air.

![Diagram](image)

**Figure 2.** The physical model of induction heating of composite hot-plate.

**Table 1.** The thermal and physical properties.

| Material | Temperature (°C) | Specific heat (J/kgK) | Thermal conductivity (W/mK) | Relative permeability | Resistivity $(10^{-6} \Omega)$ |
|----------|------------------|-----------------------|----------------------------|-----------------------|-----------------------------|
| S45C     | 20               | 472                   | 47.68                      | 200                   | 0.20                        |
|          | 100              | 480                   | 43.53                      | 195                   | 0.25                        |
|          | 200              | 498                   | 40.44                      | 186.6                 | 0.34                        |
|          | 300              | 524                   | 38.13                      | 178.1                 | 0.43                        |
| Aluminum | 900              | 238                   | 1                          | 1                     | 0.27                        |
4. Results and discussion
The proposed model was simulated by COMSOL under the process conditions of the parameters (the distance between coil and bottom surface of the hot-plate is set to 5mm, the current is set to 850A, the frequency is set to 70KHz). Figure 4 describes the simulated profile of average temperature and temperature difference versus time on the target surface of the hot-plate without and with holding current. As can be seen from Figure 4, the average temperature and the temperature difference on the target surface of the composite hot-plate with holding current have been significantly reduced. In addition, the heating speed of composite hot-plate is faster than that original hot-plate with S45C steel due to differences in material parameters with a high thermal conductivity.

Unfortunately, the hot-plate temperature profiles colored in blue and black shown in Figure 4(a) have been raising gradually and cannot be stabilized at the target temperature without any reduction of the current shown in Figure 5(a). To solve this problem, it is necessary to reduce electrical current after the larger current is kept a certain period of time shown in Figure 5(b). As can be seen in Figure 4(b), the temperature differences on the target surface with smaller holding current is less than 2°C as the holding time arrives at about 500s. Obviously, the average temperature on the target surface of the hot-plate is finally stabilized numerically at 180°C and the temperature difference is close to 0°C as shown in Figure 4.
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![Current Graphs](image)

(a) without holding current setting  
(b) with holding current setting

**Figure 5.** Electrical current setting.

Figure 6 shows the temperature distribution on the target surface of the hot-plate with and without holding current setting. It is observed that the uniform and stable temperature distribution on the target surface of the hot plate can be achieved using the proposed strategy of composite hot-plate and holding current setting.

![Temperature Distribution](image)

(a) original hot-plate without holding current  
(b) composite hot-plate without holding current  
(c) composite hot-plate with holding current

**Figure 6.** The temperature distribution on target surface of the hot-plate.

In summary, the study to obtain stable and uniform temperature distribution of hot-plate during induction heating process can be divided into two stages. Firstly, a thin layer of S45C steel is coated on the surface opposite to electric coil. Due Joule heating effect, the temperature at this thin layer will increase but be distributed unevenly. To obtain uniform temperature distribution, the aluminium alloy with excellent thermal conductivity is employed to make the main body of the hot-plate to form composite hot-plate. Then, the strategy with holding current setting is employed to achieve stable target temperature on the target surface of the hot-plate.

5. **Conclusions**

In this paper, to meet the industrial requirements, a new composite hot-plate is proposed according to the electromagnetic heating theory. Based on this proposed strategy, it can be concluded that the scheme can effectively reduce the temperature difference on the surface of the hot-plate, so that the stable and uniform temperature distribution of the hot-plate can be achieved.
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