Study on Mechanism of Heating Temperature Field of Aluminum Foil Seal

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Abstract. The theoretical basis for non-contact sealing detection is lacking for the sealing performance of aluminum foil sealing. First, simulation and analysis of heat transfer characteristics of aluminum foil seals in heating temperature field using ANSYS software. The temperature field image sealed by aluminum foil is a closed and uniform annular region with high temperature. In the temperature curve, the temperature is concentrated at 70–80 celsius. It has symmetry characteristics, and there are 2 high temperature peaks; the other 5 are unlooped or uneven thermal image aluminum foil seal failed. A comparative experiment was then carried out to collect infrared thermal images of different types of aluminum foil seals under electromagnetic induction heating. Experiments show that the surface temperature field distribution calculated by the three-dimensional finite element simulation is consistent with the experimental temperature-field distribution. According to the distribution characteristics of the thermal temperature field, it can be evaluated the state of the sealability of the aluminum foil seal, and it can provide theoretical support for further optimizing the automation degree of the non-contact sealability test.

1. Introduction

Aluminum foil packaging has been widely used in the packaging of pharmaceuticals, food, oil and other packaging. In the process of sealing with aluminum foil, the problem of uneven heating or defects of the aluminum foil itself is inevitable, which is easy to cause leakage and greatly affects the packaging quality of the product [1]. For the existing methods to detect the sealing properties of aluminum foil, such as differential pressure air leakage detection method, displacement leakage detection method, ultrasonic detection method, et al. [2, 3]. Although the principle is simple and the cost is low, there are certain shortcomings, the main defect is that real-time online detection cannot be realized. It is only suitable for sampling detection, low efficiency, inspection is destructive to the product, the degree of automation is low, can not quickly find the defects of the aluminum foil seal and remove in time. Therefore, it is a research hotspot in the field of aluminum foil packaging sealing detection to find a method with high detection precision, wide application range and automatic identification detection [4, 5].

In this paper, the temperature field distribution mechanism of aluminum foil surface under different sealing conditions under electromagnetic induction heating is studied. Firstly, the finite element mathematical model of induction heating theory is established, the Joule heat of induced current is...
solved and the temperature field is calculated as the internal heat source. Then, the steady-state heat conduction model of aluminum foil seal with six different sealing conditions is established through finite element method. ANSYS software was used to conduct numerical simulation analysis on the heat transfer characteristics of the aluminum foil sealing heat temperature field, and the thermal temperature field image and temperature curve corresponding to different types of aluminum foil sealing conditions are obtained. After the comparative experiment, infrared thermal images of different types of aluminum foil seals under electromagnetic induction heating were collected. The results show that the surface temperature field distribution calculated by the three-dimensional finite element simulation is in good agreement with that obtained by experiment.

2. Numerical calculation of Heat Transfer in Aluminum Foil Seal Heated by Temperature Field

2.1. Geometric model and material composition

The research object is aluminum foil and bottle mouth, the aluminum foil piece is made of pure aluminum, and the bottle mouth is made of polyethylene. In order to study the temperature field formed by the aluminum foil seal heating and to judge the sealing degree, the steady-state thermal radiation numerical model of the six sealing conditions of aluminum foil based on ANSYS finite element was established in this paper. According to the actual situation, the aluminum foil reaches 80 celsius instantaneously under the heating of the sealing machine. Since the aluminum foil is in contact with the bottle body, the heat can be quickly transferred to the bottle mouth portion, so the center temperature of the aluminum foil is the highest, as shown in Fig.1. In this paper, the aluminum foil and the bottle mouth are selected to establish a finite element analysis model. The nominal diameter of the aluminum foil is 30 millimeter, the thickness is 0.01 millimeter, the outer diameter of the bottle mouth is 28 millimeter, the inner diameter is 24 millimeter, and the height is 10 millimeter. The ANSYS pre-processing software Geometry is used to build a three-dimensional model, and then the model is meshed into hexahedral elements with a mesh size of 0.05 millimeter.

![Figure 1](image)

**Figure 1.** Calculation model diagram of electromagnetic induction heat radiation and conduction.

2.2. Numerical Simulation Calculation

Electromagnetic induction heating process is the energy conversion between electric energy and magnetic energy, and finally converted into the internal energy of aluminum foil to complete the heating of aluminum foil. According to Faraday's electromagnetic induction law [6, 7].

\[
\begin{align*}
\phi &= BS \\
B &= \mu H \\
\varepsilon &= N \left( \frac{\delta \phi}{\delta t} \right)
\end{align*}
\]

(1)
So

$$\varepsilon = \mu N S \left( \frac{\partial H}{\partial t} \right)$$  \hfill (2)

Where \( \Phi \) is the magnetic flux (Wb) generated by the induction coil; \( B \) is the magnetic induction (T); \( S \) is the cross-sectional area of the coil (mm²); \( \mu \) is the permeability of the medium; \( H \) is the magnetic field strength (A/m); \( \varepsilon \) is the induced electromotive force (V); \( N \) is the number of turns of the coil; \( N \) and \( S \) are constants.

The magnitude of \( H \) depends on the source of the magnetic field excitation, that is, the rate of change of the magnetic field strength over time \( \frac{\partial H}{\partial t} \) is determined by the current intensity and frequency in the coil.

$$I = \varepsilon / R$$
$$P = I^2 R$$
$$R = \rho L / S$$
$$Q = P t = I^2 R t$$  \hfill (3)

Where \( I \) is the eddy current size (A); \( R \) is the resistance value (Ω); \( \rho \) is the resistivity (Ω·m); \( S \) is the cross-sectional area (m²); \( L \) is the length (m) of the wire; \( c \) is the specific heat capacity [J/(kg·K)]; \( m \) is the mass (kg).

Given the magnitude and frequency of the current, the joule heat is calculated and calculated as an internal heat source. During induction heating, the temperature distribution of aluminum foil has a functional relationship with coordinates and time, that is [8, 9]:

$$T = f(x, y, z, t)$$  \hfill (4)

Where \( x, y, z \) is the space Cartesian coordinates, \( t \) is the time coordinate.

The distribution of the temperature inside the aluminum foil when the induction heating is completed is obtained, that is, the temperature field of the aluminum foil when the heating is stopped is studied. Establish the differential equation of heat conduction in cylindrical coordinate system:

$$\frac{\rho c}{r} \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \lambda k \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left( \lambda \frac{\partial T}{\partial \theta} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + \phi$$  \hfill (5)

Where \( T \) is the transient temperature (K) of the object; \( \rho \) is the material density (kg/m³); \( \lambda \) is the thermal conductivity [W/(m·K)] of the material; \( c \) is the material specific heat [J/(kg·K)]; \( \phi \) is the heat (J) generated by the internal heat source.

Since aluminum foil is symmetrical, that is, \( \partial T / \partial \theta = 0 \), and the thickness of aluminum foil is negligible, the basic mathematical model for solving the temperature field can be:

$$\frac{\rho c}{r} \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \lambda k \frac{\partial T}{\partial r} \right) + \phi$$  \hfill (6)

2.3. Initial Conditions and Boundary Conditions

The aluminum foil in the model is pure aluminum, and the mouth of the bottle is made of polyethylene. The subject of the research is aluminum foil, that is, the temperature change of the aluminum foil when it is heat sealed. The bottle mouth and aluminum foil are selected from the parameters of polyethylene and pure aluminum in the ANSYS material library. The steady-state temperature analysis module is selected. The aluminum foil in the model is a metal material with a small thickness, so it can be regarded as an infinite large plate. Therefore, the finite element analysis of the aluminum foil subjected to heat sealing is a contact problem. Due to the tangential relative sliding between the aluminum foil surface
and the air, and the normal contact with the bottle mouth, the relevant contact surface of the air and the aluminum foil, and the relevant contact surface of the aluminum foil and the bottle mouth are set to frictional contact in the setting. The friction factor is 0.26, and the contact algorithm uses the Lagrange enhancement algorithm, and to set the outer surfaces of the aluminum foil in contact with each other. Compared with the extremely thin aluminum foil, the mouth portion is set as a rigid body, and the deformation can be ignored. Then, the aluminum foil is set to be fixed, and the heat source continues to radiate heat downward, eventually sealing the aluminum foil to the finish.

The initial condition of the induction heating temperature field refers to the temperature of the object in the entire space at the beginning of heat transfer. At the beginning of induction heating, the initial temperature of the aluminum foil is uniform, that is, the initial condition is [10]:

\[ T(x, y, z, 0) = T_0 \]  

(7)

The sealing process of aluminum foil by electromagnetic induction heating is accompanied by three heat transfer modes: heat conduction, convection and radiation. The boundary condition of the governing equation is [11]:

\[-\lambda \frac{\partial T}{\partial n} + h(T_e - T_v) + \sigma e(T^4 - T_v^4) = q_s(x, y, z, t)\]

(8)

Where \( q_s \) is the heat per unit area (W/m²); \( \lambda \) is the thermal conductivity [W/(m·K)]; \( h \) is the convective heat transfer coefficient; \( n \) is the direction of the normal outside the boundary; \( T_v \) is the temperature (K) of the surface of the aluminum foil; \( T_e \) is the ambient temperature (K); \( e \) is the thermal emissivity, constant, about \( 5.67 \times 10^{-8} \text{W/(m}^2 \cdot \text{K}^4) \).

3. Simulation Results and Analysis

Figure 2. Temperature field images of six sealing conditions based on ANSYS simulation.
In the actual processing process, the aluminum foil sealing is generally realized by an aluminum foil sealing machine. The principle is that the electromagnetic induction heating causes the temperature to rise instantaneously. The temperature of the electromagnetic induction heating is generally at 200 celsius. After the product is taken out of the sealing machine for 30 seconds, infrared thermal imaging is conducted, and the temperature of the aluminum foil is about 80 celsius when the thermal imaging image is obtained. In order to simulate the actual situation, when ANSYS analyzes the heated temperature field of the aluminum foil seal, the heat source is set to a fixed 80 celsius, and the temperature field of the aluminum foil seal is simulated, as shown in Fig. 2.

Then, according to the actual thermal image obtained, this paper takes the diameter of aluminum foil as the x-coordinate, the temperature as the y-coordinate, and the center of aluminum foil as the coordinate origin to draw the temperature distribution curve, as shown in Fig. 3. According to the temperature field image and temperature curve, it can be roughly divided into the following two cases, one of which is a temperature field image in which a uniform annular region is closed at a high temperature, and the other five are the temperature field images which are not looped or looped unevenly. Through the comparison of the temperature curves, it can be clearly seen that the temperature curve of aluminum foil, which is well-sealed, is between 70–80 celsius in the high temperature section and has two high temperature peaks, which are symmetrically distributed. Although the temperature curve of aluminum foil with uneven thermal distribution and perfect sealing is concentrated between 70–80 celsius, and has two high temperature peaks, its temperature distribution is asymmetric, and the temperature between 0–5 millimeter is obviously lower than the sealed temperature of aluminum foil. In addition, the temperature curves of the other four sealing conditions are mostly asymmetrical, and both have only one high temperature peak. The minimum temperature of the other three sealing conditions is lower than 70 celsius, except for the case of aluminum foil without bottle cap, which is higher than 70 celsius. Therefore, according to the temperature curve comparison chart, the six sealing conditions of the aluminum foil can be directly judged by the temperature range, the symmetry, and the minimum temperature.

Figure 3. Five kinds of sealing defects and sealing good temperature contrast chart.
4. Design Experiment Comparison

4.1. Thermal Image Acquisition Process
In order to verify whether the simulation calculations are consistent in practical application, and further study on how to judge the existence and characteristics of sealing defects according to the characteristics of thermal image in aluminum foil sealing detection, this paper designs a comparative experiment of sealing defects detected by infra red thermal imaging. Through the research of the researchers in the literature on the detection of aluminum foil sealing defects, the infrared thermal imaging detection experiment was designed, and the experimental scheme was developed according to the existing equipment. The camera is placed at a fixed position of 800 millimeter behind the heating device and 150 millimeter from the bottle cap. Image acquisition is performed for each target passing through this position. In order to ensure that only one temperature of each thermal image is collected, it is necessary to obtain the temperature. The same heating time and cooling time should be ensured to each acquired target. At the same time, the focal length and other parameters of the thermal imager remain unchanged during the thermal image acquisition process. The image of each target passing through the position was acquired, and a large number of aluminum foil seal thermal images were taken as samples for comparison experiments. In order to facilitate the comparison between the experimental and simulation results, the experimental parameters should be consistent with the simulated calculation values.

4.2. Thermal Image Type
The experimental image data in this paper was taken with the American Fluke Ti40 thermal imaging camera. By collecting a large number of thermal images of the caps on the assembly line, six common types of different thermal image images are generally summarized. The corresponding thermal images of the six different sealing conditions are shown in Fig. 4.

![Thermal Image of six different aluminum foil seals.](image)

(a) uneven heat but good seal (b) uneven heat and poor seal (c) only aluminum foil without bottle cap (d) aluminum foil damaged (e) no aluminum foil (f) aluminum foil seal intact

Figure 4. Thermal image of six different aluminum foil seals.

4.3. Contrast Experimental Conclusion
In the comparative experiment of the experimental results and the simulation results, the experimental parameters are the same as the boundary conditions of simulated heat conduction, and the heat conduction parameters are consistent. It can be seen from Fig. 5 that the surface temperature field distribution calculated by the two-dimensional finite element simulation is in good agreement with the experimental temperature field distribution. Infrared detection temperature is affected by environmental radiation and surface material properties, but for infrared images of the same material, environmental radiation and
surface material properties do not affect the temperature difference between pixels, and therefore more accurately reflect the object than the temperature curve. Therefore, the results of temperature field simulation by using finite element method are in good agreement with the experimental results.

5. Conclusion
In this paper, the shortcomings and defects of the current aluminum foil sealing and sealing detection system are analyzed, and the effects of different sealing conditions of aluminum foil on the surface temperature distribution of aluminum foil during electromagnetic heating are studied. Based on the principle of induction heating, a calculation model for numerical simulation of induction heating finite element is established. A method for numerical simulation analysis of heat transfer characteristics of aluminum foil sealing heat temperature field using ANSYS software is proposed. Before the analysis, the calculation model, method and boundary conditions used in numerical analysis were verified. Through the finite element method, the transient heat conduction model of six different sealing conditions was established. Under the condition of constant temperature, the two-dimensional analysis and solution of the temperature distribution of different types of aluminum foil sealing conditions was solved, and different types of thermal temperature field distribution characteristics corresponding to different types of aluminum foil sealing conditions were obtained. Finally, the simulation analysis and infrared thermal imaging to detect the sealing defect comparison experiment were designed. The experimental results show that the temperature field calculation results of the aluminum foil sealing simulation using the finite element method are highly consistent with the experimental results. Therefore, in this paper, the products with the characteristic of the high temperature closed annular region in the temperature field can be regarded as a fully qualified product; the non-annular feature in the temperature field image is regarded as a unqualified product. The research in this paper shows that the sealing performance of aluminum foil sealing can be judged by studying the distribution characteristics of thermal temperature field, which can provide theoretical support for further optimizing the automation degree of non-contact sealing detection.

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