Microwave-heating characteristics of ferrite-particle-containing silicone

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Abstract: In this paper, we quantified the permittivity and permeability of ferrite-particle-containing silicone using a perturbation method with a harmonic resonator and investigated whether the modified silicone can be used as a material for fabricating heating vessels for microwave ovens. The material constant varied depending on the compounding ratio of the obtained ferrite. From our simulation results using a microwave oven model, we confirmed that the container was well heated and that the food in the container was heated by the remaining energy.

Keywords: microwave heating, absorber, dielectric loss, magnetic loss, cavity resonator, harmonic resonator

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

In the recent years, microwave ovens have become useful as convenient heating and cooking machines because microwaves are absorbed by the moisture in food, which results in heating. In other words, the dielectric loss of the dielectric food is the factor of heating. A material with a low dielectric loss tangent, such as glass or silicone, is typically used as food containers because food heating is more efficient if the container absorbs no energy. For example, silicone steamers are containers fabricated from silicone resin; they can conveniently cook vegetables by steaming. The steam is generated from the vegetables being heated inside the sealed container. Microwave ovens are, therefore, widely used for cooking foods but not for baking them. In this paper, we propose ferrite-particle-containing silicone (Fig. 1) as a material for fabricating heating containers that can bake food surfaces at a high temperature and transfer the heat to the interior of the food, similar to cooking in a pan. We describe possible applications of this technology.

Fig. 1. Ferrite-particle-containing silicone.

2 Microwave-heating theory of metal powder

Microwave heating selectively responds to only electric or magnetic field components for each substance. The dielectric is heated in response to the electric field component because of the vibrations of polarized minute molecules. In contrast, a ferromagnetic material such as iron is heated by a magnetic field component. When a metal has no magnetism, a bulk plate almost completely reflects microwaves, but metal particles can be heated by microwaves by their magnetic field components [1, 2, 3]. This is because the magnetic field penetrates into the particle and

induces eddy currents to become Joule heat. Microwaves do not permeate through continuous metallic bodies because of the skin effect, but in the case of particles, they can be heated for a large surface area.

Previous studies have reported metal powders (Al, Co, Cu, Fe, Mo, and Zn) capable of being heated by microwaves [4], and there have been examples in which bulk alloys (Fe–Cu/Ni–C and Co) were sintered by metal powder heating [5]. Microwave heating of Titanium (Ti) has also been demonstrated [6].

The heating rate per unit volume from microwaves P can be calculated as follows:

$$P = \frac{1}{2} \omega \varepsilon_0 \varepsilon'' |E|^2 + \frac{1}{2} \omega \mu_0 \mu'' |H|^2 + \frac{1}{2} \sigma |E|^2$$

where ω is the angular frequency, σ is the electric conductivity, ε_0 is the dielectric constant in vacuum, ε'' is the imaginary part of the relative permittivity, μ_0 is the magnetic permeability in vacuum, μ'' is the imaginary part of relative permeability, $|E|$ is the electric field inside the material particle, and $|H|$ is the magnetic field inside the material particle. The first term on the right hand side of the equation is the dielectric loss, the second term is the magnetic loss, and the third term is the Joule loss. Joule loss occurs eddy current of magnetic field energy penetrates into metal particle. Metal particles of sub-micron size produce fine powders whose electric conductivities are orders of magnitude smaller than those of bulk metal, so they can be combined with microwaves and heated. In fact, the surface of the metal is covered with an oxide film, which causes large radiation loss and impedes heating [7]. It is, therefore, desirable that the surface oxide film is removed. When the radius of the metal particles is about twice the skin depth δ , Mie theory dictates that the heating rate becomes maximum [8].

3 Material constant of ferrite-particle-mixed silicone

In this work, magnetic ferrite powder was selected as a material. This is because metal magnetism is well heated to the heating function compared with non-magnetic Ti. If the surface of the container is heated then the remainder of the energy needs to be transmitted to the interior moderately. Therefore, using the silicone steamer, we analyzed a container fabricated from a material mixed with ferrite particles in silicone. Three types of materials were prepared with ferrite particle of sizes of 4–5 μm and 25%, 50%, and 75% by weight, respectively (Fig. 2).

Fig. 2. Ferrite-particle-containing silicone sheet.

The Nicolson–Ross–Weir (NRW) method [9, 10] is widely used to evaluate permittivity and permeability. The perturbation method [11] with a cavity resonator can only measure a single frequency and is not suitable for the measurement of large permeabilities. However, in the perturbation method, precision is guaranteed for NRW method because the material constant of the standard sample is used and the reliability of the data can be confirmed.

Here, the characteristics were evaluated by a perturbation method [12] using a harmonic resonator with a long rectangular waveguide and a fundamental harmonic resonance mode generated inside the waveguide. In this manner, evaluation of the complex permittivity and permeability is possible over a wide range. The sample was inserted into a hole at the center of the waveguide. The hole at the center of the H plane was for measured for permeability, and the hole at the center of the E plane was measured for permeability. The dielectric constant was obtained from the change in the resonance characteristics, dependent upon the presence or absence of the sample, by placing the sample at the maximum electric field inside the waveguide resonator where the magnetic field was minimum. Conversely, the magnetic permeability was obtained by placing the specimen at the position of the maximum magnetic field and the minimum electric field. The evaluation system is explained in Fig. 3. Network analyzer model is 8510C (Keysight).

$$\begin{aligned}\varepsilon' &= 1 + \frac{V}{\alpha \Delta V} \left(\frac{F_0 - F_s}{F_0} \right) \\ \varepsilon'' &= \frac{V}{2\alpha \Delta V} \left(\frac{1}{Q_s} - \frac{1}{Q_0} \right) \\ \mu' &= 1 + \frac{V}{\alpha \Delta V} \left(\frac{F_0 - F_s}{F_0} \right) \\ \mu'' &= \frac{V}{2\alpha \Delta V} \left(\frac{1}{Q_s} - \frac{1}{Q_0} \right)\end{aligned}$$

F is the resonance frequency and Q is the Q value of the resonator. The suffix 0 represents the empty resonator without the sample, whereas the suffix s represents the resonator into which the sample is inserted. α is the proportionality constant of the resonance mode, V is the volume of the resonator, and ΔV is the sample volume.

Fig. 3. Structure of harmonic resonator [12].

Results of the evaluation are shown in Fig. 4. As the compounding ratio of ferrite increased, the permittivity and permeability also tended to increase. ϵ' and ϵ'' showed a monotonous increase with increasing frequency. This is a feature found in materials in which metal is kneaded in an insulator (resin). We think that the increase of ϵ'' is caused by the increase in resistance as the skin depth decreases.

μ' showed monotonous decrease with increasing frequency. Above 6 GHz, $\mu'' < 1$. We believe that this is influenced by the skin effect of metallic magnetic materials. When $\mu'' < 0$, it becomes a noise radiation source and not an absorber. This is caused by natural resonance and rarely occurs in a carbon absorber. It was confirmed that this sample has broadband absorption characteristics.

During these measurements, polarization phenomena caused by opposing electromagnetic fields occur at both end surfaces of the inserted sample, so it is necessary to correct the measurement data by normalization. From our results, it is confirmed that the discontinuity point is eliminated by the correction.

Fig. 4. Measurement results of material constant (25%, 50%, and 75%).

4 Microwave-heating simulation

We selected meat as an evaluative material and conducted a heating simulation in our microwave oven model. The simulation software is ANSYS 18.1. The material constants at 2.4 GHz are shown in Table I. The size of the microwave oven was $290 \times 290 \times 200 \text{ mm}^3$. The heating container had an outer size of $150 \times 150 \times 100 \text{ mm}^3$ and a thickness of 2 mm. In the simulation, the container was filled with meat. The simulation model, shown in Fig. 5, is a one-port model, and all input energy except reflection is consumed by Sheet and meat. The percentage energy consumption is shown in Table II, and the simulation result is shown in Fig. 6, in which the input port is assumed to be on the upper left. Input power is 500 W. As the ferrite mixing ratio increased, the energy consumption rate in the container increased and the internal consumption rate decreased. This is because ferrite absorbs some magnetic field energy as heat, and the remainder passes inside. The meat inside is heated by electric field energy. In the lower right part of Fig. 6, it seems that the power consumption is small, but in practice, the unevenness in heating is eliminated because of turntable rotation.

Table I. Material constant at 2.4 GHz

Material	ε'	$\varepsilon''/\varepsilon'$	μ'	μ''/μ'
25% Sheet	5.270	0.037	1.188	0.151
50% Sheet	9.008	0.047	1.448	0.389
75% Sheet	21.433	0.076	1.797	0.920
Meat	52.0	0.35	1.0	0

Table II. Energy consumption rate of container and meat

	25% Sheet	50% Sheet	75% Sheet
Container	12.6%	29.3%	52.9%
Meat	81.8%	64.9%	40.3%
Total	94.4%	94.2%	93.3%

Fig. 5. Microwave internal simulation model.

Fig. 6. Simulation results (25%, 50%, and 75%).
xy-plane in $z = 0$ (center of the meat)

5 Conclusion

In this paper, we have quantified the permittivity and permeability of ferrite-particle-containing silicone using the perturbation method with a harmonic resonator and investigated whether the modified silicone can be used as a material for fabricating heating vessels for a microwave oven. Using our simulation results, we confirmed that the container and the food inside were both heated and that the ferrite-particle-containing silicone could be used for cooking. If a container is only dielectric, it cannot be heated. Metal containers cannot be used to heat food, so we developed a container that uses a new heating mechanism. The relationship between the ferrite mixing ratio and the energy consumption rate was explored, but the design of the container will depend on its application.

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