Measurement of the Dielectric Properties of Micaceous Minerals Using Scattering Parameters

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Abstract— The determination of the dielectric properties of materials is very important in the development of microwave heating systems. In this case, determining the dielectric properties of the materials to be processed is the essencial key point in order to achieve good efficiency of the system. In the present study the determination of the complex permittivity of vermiculite that is a hydrated phyllosilicate is presented. In a previous work the dielectric constant of vermiculite was determined using a TDR-based probe. In this study dielectric constant was determined through the measurement of the volumetric water content and the refractive index. Although the method demonstrated a good accuracy, it was not possible to determine the complex permittivity of the mineral due to the characteristics of the equipment used. So, in order to determine the complex permittivity using an accurate and nondestructive method, the scattering parameters were chosen. The method is based on the usage of a microstrip line and through the measurement of the S-parameters by a VNA the data was processed in MATLAB code. The results were very close to the ones obtained with the TDR probe, but now with the determination of the complex permittivity and loss tangent. The data obtained with the present study show that the determination of the dielectric properties of materials such as vermiculite using S-parameters is an accurate and nondestructive method.

1. INTRODUCTION

In studies related to mineral processing using microwave radiation, the knowledge of the material properties is extremely important to properly understand its behavior when exposed to microwaves. The complex permittivity is the most important characteristic that should be known a priori for material processing using microwave radiation. The complex permittivity provides information on energy absorption and reflection and quantifying the power losses, which in turn leads to heat dissipation and, consequently, to temperature rise. The focus of this work is on the determination of the dielectric properties of vermiculite using S-parameters. In a previous work, we used a water content probe to determine the dielectric constant of vermiculite in terms of the refractive index [1]. In that work we extensively explored the strong relationship existing between the material humidity and its dielectric constant. However, to properly understand how vermiculite reacts to microwave radiation it is necessary to determine its complex permittivity and therefore its loss tangent. This enables the development, in an accurate manner, of a system capable of processing vermiculite using microwaves. Among the traditional methods generally used to determine the complex permittivity of materials such as resonant cavities and open coaxial probe, the transmission line method was selected mainly for its simplicity and low cost implementation. The transmission line that was used was a microstrip line built on FR4 substrate. The frequency range of interest was from 1.6 GHz to 2.45 GHz. From the measured S-parameters using a Vector Network Analyzer (VNA), the complex permittivity was determined using a simple code developed in MATLAB based on the Nicholson-Ross-Weir (NRW) noniterative method. The results obtained show that the values for the real part of the complex permittivity are very close to the ones obtained in our previous work [1].

2. VERMICULITE

Vermiculite is defined as a layered hydrated aluminum iron magnesium calcium silicate with bond water molecules between the layers. Typical exfoliation rates vary from 8 to 12 in volume but can reach a value of up to 30, or more. The humidity of the raw material and potassium (K) amounts can also interfere in the final exfoliation rate [1]. The traditionally used method of exfoliating vermiculite is heating by means of direct or indirect flame (800°C to 1000°C). This method leads to high material losses with significant production of gangue, and the process causes chemical alterations of the oxides minerals contained in the structure.

Vermiculite can be exfoliated by microwave radiation. In this method the oxides are not appreciably heated because microwave radiation heats primarily the interlayer water molecules present in the structure, the integrity of the oxides is almost maintained.

3. METHODOLOGY

3.1. Transmission Line Method

The reflection method to measure the complex permittivity of materials is based on the measurement of the reflection coefficient on the interface between a microstrip transmission line and a material under test (MUT). The reflection coefficient of a microstrip transmission line depends on the complex dielectric permittivity of the vermiculite sample. Many reasearchers have measured the permittivity of different types of lossy materials [2]. The ε_{ff} depends on the fields in the material and the fringing fields along the structure of the microstrip line. In some cases the effective permittivity is coupled model [3] and [4] and can be used to obtain the complex permittivity [5] and [6]. Dielectric losses in the material are usually difficult to measure with transmission lines structures such as microstrip lines. Using resonant microstrip lines or striplines makes it possible to obtain a more accurate determination of the loss tangent which increases the reliability of the method.

3.2. Nicholson-Ross-Weir Method

The Nicholson-Ross-Weir equations is a widely used method to calculate the complex permittivity and permeability of unknown material samples from the measured S-parameters.

In this method S_{11} and S_{21} are expressed in terms of two quantities Γ_1 and z whose values depends on the complex permittivity and permeability of the vermiculite samples. The calculation of Γ_1 and the material dielectric properties is made by adding and subtracting the measured S-Parameters as follows:

$$V_1 = S_{21} + S_{11} \tag{1}$$

$$V_2 = S_{21} - S_{11} \tag{2}$$

The reflection coefficient is given by:

$$\Gamma_1 = X \pm \sqrt{X^2 - 1} \tag{3}$$

where the term X is given by:

$$X = \frac{1 - V_1 V_2}{V_1 - V_2} \tag{4}$$

Considering $|\Gamma_1| \leq 1$ is important in order to give the physically possible solution.

The permeability μ of the material is given by

$$\mu_r = \frac{1 + \Gamma_1}{(1 - \Gamma_1)\Lambda\sqrt{\frac{1}{\lambda_0^2} - \frac{1}{\lambda_C^2}}} \tag{5}$$

where λ_0 is the wavelength in free space. λ_C is the wavelength at the cutoff frequency in the microstrip transmission line.

Considering the vermiculite permeability $\mu_r = 1$.

The complex permittivity can be calculated by:

$$\varepsilon_r = \lambda_0^2 \left\{ \frac{1}{\lambda_C^2} - \left[\frac{1}{2\pi L} \ln\left(\frac{1}{Z_1}\right) \right]^2 \right\} \tag{6}$$

where

$$\ln\left(\frac{1}{Z_1}\right) = \gamma d \tag{7}$$

In Equation (10) the natural logarithm of a complex number must be calculated. This implies to appropriate choose the correct root for the determination of the complex permittivity and permeability of the material.

3.3. Microstrip Line

In developing the microstrip line the following relationship between the width of the strip and height was considered.

$$a = W/h > 1 \tag{8}$$

where W is the width of the strip. h is the height of the substrate.

The output impedance of the microstrip transmission line was determined considering the following equation [9]:

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{eff}}} \cdot \frac{1}{a + 1.393 + 0.667 \cdot \ln(a + 1.444)} \tag{9}$$

Considering $\varepsilon_r = 4.6$ for the FR4 substrate the effective permittivity ε_{ff} is then

$$\varepsilon_{eff} = \left(\frac{120\pi}{50} \cdot \frac{1}{1.787 + 1.393 + 0.667 \cdot \ln(1.787 + 1.444)}\right)^2 \tag{10}$$

For a microstrip matched to an impedance of $50\,\Omega$ the effective permittivity is $\varepsilon_{eff} = 3.62$.

A simulation of the microstrip transmission line using CST MW Studio™ was made to use the results as a parameter to compare the results obtained during the measurements.

4. RESULTS

The sample of vermiculite was placed in a microstrip transmission line and the values for S_{11} and S_{21} were obtained with a VNA. The complex permittivity of the sample was determined by a code developed in MATLAB™ for the numerical calculation of the complex permittivity. The results were compared to results obtained in CST MW Studio™.

Tables 1 and 2 present the results of the measurement and the ones obtained through the simulation in CST MW Studio™.

Table 1: Results of the measurements.

Frequency (GHz)	**Complex permittivity of the vermiculite sample**		
	Complex permittivity ε_r	$\lvert\varepsilon_r\rvert$	*Tanδ*
1.6	4.19-j0.16	4.18	0.03
1.8	4.18-j0.20	4.18	0.04
2.0	3.55-j0.43	3.58	0.12
2.45	3.50-j0.44	3.53	0.13

Table 2: Results of the simulation.

Frequency (GHz)	**Complex permittivity of the vermiculite sample**		
	Complex permittivity ε_r	$\lvert\varepsilon_r\rvert$	*Tanδ*
1.6	4.29-j0.17	4.29	0.04
1.8	4.26-j0.36	4.27	0.05
2.0	4.24-j0.42	4.26	0.10
2.45	4.18-j0.45	4.20	0.11

5. CONCLUSION

The absolute values for the permittivity obtained with the method presented were very close to the ones obtained in a previous study done using a TDR probe and in the simulations made in CST MW Studio™. The The use of the described method employing a microstrip line and scattering parameters is a very useful and low cost nondestructive tool for the determination of the complex permittivity of minerals and more specifically of phyllosilicates.

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