Complex permittivity of FeSiAl/Al_2O_3 ceramic composite at X-band frequencies

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Abstract. The objective of this paper is to extract and study the complex permittivity of the FeSiAl/Al_2O_3 ceramic composite at X-band frequencies. We studied by simulation the complex permittivity of four composites with FeSiAl content varying from 0% to 15% by volume in the alumina matrix. The influence of the FeSiAl content on the complex permittivity of the FeSiAl / Al_2O_3 composite was also studied. The results obtained show on the one hand that the complex permittivity depends on the frequency. Indeed, the values of the real and imaginary parts of the complex permittivity decrease with the increase in frequency over the entire frequency range in the X band. On the other hand, the high FeSiAl content has a significant impact on the values of the real and imaginary parts of complex permittivity. Higher values were obtained for composites with a high inclusion content. In this work, we obtained a good agreement between the simulation results and the published experimental results. These results indicate that the FeSiAl / Al_2O_3 composite can be used in applications as an electromagnetic wave absorbing material.

1 Introduction

In recent years, great importance has been given to the study of ceramic composite materials. Alumina matrix composites are among the materials that have attracted the attention of researchers [1, 2, 3, 4].These materials have been used in many areas, especially in commercial, civil and military fields [5]. Due to the higher dielectric properties and excellent microwave absorption properties possessed by these materials, they have also been used in devices absorbing waves emitted by radars RAM [6], in electronic equipment, mobile communications [7], aircraft stealth technology and electromagnetic interference protection [8].

The use of materials in applications requires accurate knowledge of the complex permittivity [9]. In the literature, several methods have been used for the extraction of the complex permittivity of materials [9]. The transmission/reflection method (T/R) is the most adopted in the characterization of microwave materials [10, 11], due to its wide frequency band characterization.

The high electrical conductivity of FeSiAl material and its high permittivity, as well as their good temperature stability [12, 13] allowed its use in the reinforcement of ceramic composites for the improvement of microwave absorption properties [14], and for the design of electromagnetic wave absorbing materials. Recently, the dispersion of FeSiAl particles in the alumina matrix has resulted in the FeSiAl/Al_2O_3 composite, which has higher dielectric properties and excellent microwave absorption properties [1].

In this work, the dielectric property of the FeSiAl / Al_2O_3 ceramic composite has been studied by simulation. The aim is to determine the complex permittivity in the frequency range from 8.2GHz to 12.4 GHz (X-band). We studied four concentrations of FeSiAl that vary from 0% to 15% by volume in the Al_2O_3 alumina matrix. The adopted method is transmission/reflection (T/R) based on rectangular waveguides and which offers a characterization on a wide range of frequencies. Using a program in MATLAB, the complex permittivity can be calculated from the transmission and reflection coefficients that are extracted by the electromagnetic simulation software.

2 Theory and method

In the microwave frequency range, the transmission/reflection (T/R) characterization method has been used to determine the complex permittivity of composite materials [15].The transmission / reflection measurement cell is shown in figure 1. This cell is a rectangular waveguide WR-90, with a section (22.86x10.16) mm^2, which is used for the characterization of a dielectric material in X-band. The sample of the material under test (MUT), with a thickness of 10 mm, is inserted in the middle in a section of the guide.

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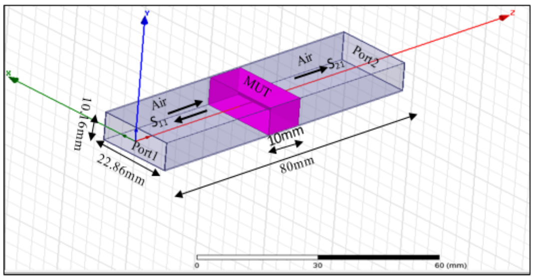

Fig. 1. Schematic of the rectangular waveguide configuration used for the extraction of material parameters in the X-band.

In this case, the dominant fundamental mode (TE_{10}) is the only one that propagates inside the cell. The complex permittivity was determined by this technique from the calculated reflection coefficient S_{11} and transmission coefficient S_{21}. The Nicholson-Ross-Weir procedure [16, 17] was used to extract the complex dielectric permittivity using the measured values of the S_{ij} parameters. It is fast, direct, non-iterative, and applicable to waveguides and coaxial lines [18]. Moreover, it allows a wide frequency band characterization [19].

In the Nicholson-Ross-Weir (NRW) procedure, the reflection Γ and transmission coefficients T are related to the parameters S_{11} and S_{21} as follows [18, 20]:

$$S_{11} = \frac{\Gamma(1-T^2)}{1-\Gamma^2 T^2} \quad (1)$$

$$S_{21} = \frac{T(1-\Gamma^2)}{1-\Gamma^2 T^2} \quad (2)$$

From the S_{ij} parameters, the reflection coefficient Γ and the transmission coefficient T are deduced by the following equations:

$$\Gamma = K \pm \sqrt{K^2 - 1} \quad (3)$$

The condition $|\Gamma|<1$ must be verified for the physical existence of the reflection coefficient.

with:

$$K = \frac{S_{11}{}^2 - S_{21}{}^2 + 1}{2S_{11}} \quad (4)$$

and

$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma} \quad (5)$$

The relative permeability of the sample is given by equation (6):

$$\mu_r = \frac{\lambda_{0g}(1+\Gamma)}{\Lambda(1-\Lambda)} \quad (6)$$

λ_{0g} is the wavelength guided in the empty cell defined by the following expression :

$$\lambda_{0g} = \frac{1}{\sqrt{\left(\frac{1}{\lambda_0}\right)^2 - \left(\frac{1}{\lambda_c}\right)^2}} \quad (7)$$

λ_0 and λ_C represent the free-space wavelength and the cut-off wavelength, respectively. Λ is the normalized wavelength related to the transmission coefficient by the following equations:

$$\frac{1}{\Lambda^2} = \left[\frac{j}{2\pi d}\ln(T)\right]^2 \quad (8)$$

with *d* the length of the sample to be characterized.

The relative complex permittivity is given as a function of the magnetic permeability by the relation:

$$\varepsilon_r = \frac{\lambda_0{}^2}{\mu_r}\left(\frac{1}{\Lambda^2} + \frac{1}{\lambda_c{}^2}\right) \quad (9)$$

The flowchart in Figure 2 represents the algorithm proposed by Nicholson-Ross-Weir [16,21] to determine the electromagnetic parameters of a dielectric material from the Sij coefficients.

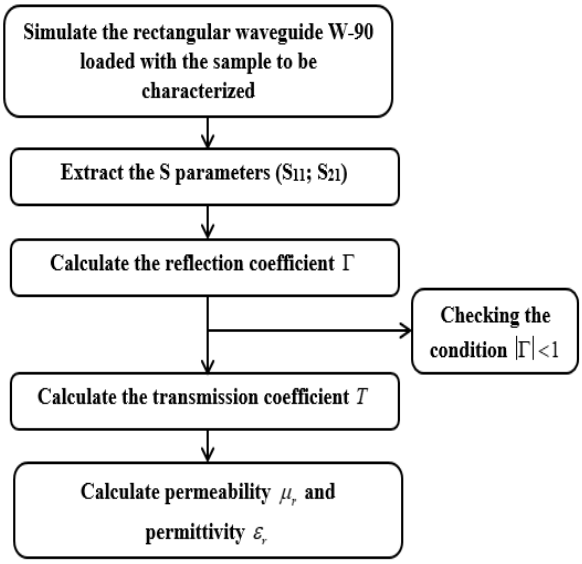

Fig. 2. Operating process of the algorithm proposed by Nicholson-Ross-Weir.

3 Results and discussion

In this part, we extracted the complex permittivity of the FeSiAl / Al_2O_3 ceramic composite in the X-band. Four samples for this composite were studied with concentrations 0%, 5%, 10% and 15% by volume of FeSiAl. Using the transmission / reflection technique, the reflection coefficients S_{11} and transmission coefficients S_{21} were extracted by simulation of the rectangular waveguide in Figure 1.The application of the NRW algorithm allows the calculation of the complex permittivity of the FeSiAl/Al_2O_3 ceramic composite in the frequency range from 8.2GHz to 12.4GHz. Figures 3a and 3b represent respectively the frequency evolution of the real and imaginary parts of the complex permittivity for the four FeSiAl contents of the material studied in the X-band.

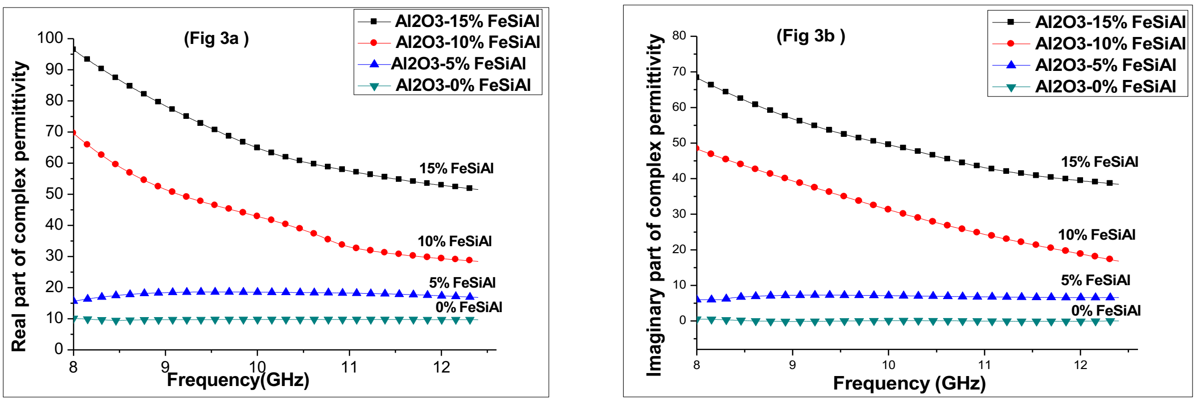

Fig. 3. Complex Permittivity of FeSiAl /Al_2O_3 ceramic composite with different FeSiAl contents in the X-band. Fig (3a) Real part, Fig (3b) Imaginary part.

Table 1 presents the values of the real and imaginary parts of the complex permittivity of the ceramics studied at 8.2 GHz. The values obtained by simulation in this work will be compared with the published experimental values.

Table 1. Values of the real and imaginary parts of the FeSiAl/Al_2O_3 ceramic for different FeSiAl contents at 8.2 GHz

	Simulated value of ε'	**Approximate value of ε' in the literature [1]**	**Simulated value of ε''**	**Approximate value of ε'' in the literature [1]**
Al_2O_3- 0% FeSiAl	9.67	9.5	0,42	0.50
Al_2O_3- 5% FeSiAl	16.88	16	5.98	3.5
Al_2O_3- 10% FeSiAl	68.48	70	44.53	44
Al_2O_3- 15% FeSiAl	86.58	85	65.40	65

Table 1 shows that the values of the real and imaginary parts of the permittivity obtained in this work are very close to the experimental values published in the literature [1]. This means the existence of a good agreement between the results of the numerical simulation and the experimentally measured values.

The curves of figures 3a and 3b show on the one hand that the content of the inclusions has an important impact on the dielectric property of the composite studied. As the concentration of inclusions increases in the composites, the values of the real and imaginary parts increase. On the other hand, the values of the real and imaginary parts of the complex permittivity decrease with increasing frequency in the X-band. The results indicate that the dielectric property of composites is frequency dependent. This behavior can be explained by the Debye theory [22]:

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_S - \varepsilon_\infty}{1 + \omega^2 \tau^2} \qquad (15)$$

where ε_s is the static permittivity, ε_∞ is the relative permittivity at the high frequency limit, $\omega = 2\pi f$ is the angular frequency, and τ is the polarization relaxation time which depends on temperature. According to equation (15), it is reasonable that the values of ε' decrease with increasing frequency as shown in Figure (3a).

Table 2 shows the values of the real and imaginary parts of the complex permittivity obtained in the work of Liu, Y et al [23]. These results were obtained experimentally for different ZrB_2 contents in the ZrB_2/Al_2O_3 composite at 8.2 GHz.

Table 2. Approximate values of the real and imaginary parts of the complex permittivity of the ZrB_2/Al_2O_3 ceramic for different ZrB_2 content at 8.2 GHz obtained in the literature [23].

	Approximate value of ε' in the literature [23]	Approximate value of ε'' in the literature [23]
Al_2O_3- 0%ZrB_2	7.20	0.50
Al_2O_3- 5%ZrB_2	11.25	1.60
Al_2O_3- 10%ZrB_2	16.50	3.30
Al_2O_3- 15%ZrB_2	21.00	4.85

Comparison of the values in Tables 1 and 2 shows that composites based on alumina reinforced with FeSiAl inclusions have higher real and imaginary part values than composites reinforced with ZrB_2 inclusion. This indicates that the reinforcement of composites by FeSiAl particles has a significant impact on the complex permittivity. This makes it possible to obtain high values of the complex permittivity and its efficient improvement.

4 Conclusion

In this work, we used the transmission/reflection method (T/R) to extract the complex permittivity of the FeSiAl / Al_2O_3 composite in the X-band. The simulation of the rectangular waveguide allows to extract the S_{ij} parameters and using the Nicholson-Ross-Weir (NRW) algorithm, we determined the complex permittivity of the composite studied. The real and imaginary parts of the complex permittivity increase in the frequency range from 8.2GHz to 12.4 GHz with increasing FeSiAl content. They decrease with increasing frequency over the entire frequency range of the X-band. This exhibits a frequency-dependent dielectric response, especially when the composite is filled with a higher content of FeSiAl particles. The dielectric property of the composite studied in this work asserts that it is a good absorber of microwaves and can be used in applications as an electromagnetic wave absorbing material.

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