ELECTROMAGNETIC PARAMETERS STUDY OF MICROWAVE-ABSORBING MATERIAL FeSiAl FOR COLLINEAR LOAD OF LINAC*

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Abstract

Microwave-absorbing material is an essential part of LINAC collinear load. It is coated on the inner walls of several trailing accelerating cavities to transform the remnant microwave power into heat. Fe-85%Si-9.6%Al-5.4% alloy, which reveals low outgassing rate and high attenuation, is selected for collinear load R&D. To measure the permittivity and permeability of FeSiAl at 2856 MHz, the coaxial transmission-reflection method is adopted. The system is firstly examined by testing the hollow coaxial fixture and comparing the results with the electromagnetic parameters of the air. Measurements of two PTFE rings show that the air gaps between the fixture and samples influence the test results seriously. CST is utilized to simulate the effects on the FeSiAl measurements. Eventually a scheme of molding the samples of FeSiAl powder mixed with paraffin to form a wax mold is proposed and the permittivity and permeability of FeSiAl are derived from the electromagnetic parameters equivalent formulas of mixed medium.

INTRODUCTION

In order to ensure LINAC running safely, the remnant microwave power has to be absorbed at the end of the accelerator tube. Waveguide load is regularly adopted, but the structures would make it difficult to miniaturize the LINAC. Collinear load is a new structure of LINAC load, which consists of several accelerating cavities coaxially extending the normal accelerating tube with efficient microwave-absorbing material coated on the inner walls. The remnant power is dissipated and transformed into heat, which is carried out through cavity walls by external cooling water. Without output coupler, the structure not only brings about simplification on focusing coils installation, but also makes the construction compact and the quality of beam current improved [1].

Absorbing material is an essential part of the collinear load and its absorbing capability depends on its electromagnetic parameters [2], which would be significant to the performance of the collinear load. There are two types of electromagnetic measurement methods for microwave-absorbing materials: the network parameters method and the resonance cavity method. The resonance cavity method is fit for low loss materials, while the network parameter method is more suitable for higher loss materials. The latter consists of coaxial transmission-reflection method [3], free space method and so on. In this paper, coaxial transmission-reflection method is used to test the FeSiAl alloy which is an efficient absorbing material and prepared by Institute of Electronics, Chinese Academy of Sciences.

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THEORY OF TRANSMISSION-REFLECTION METHOD

The transmission line is a reciprocal two-port network when the sample is a homogeneous, linear and isotropic medium. As shown in Fig. 1, the electromagnetic wave transmits and reflects back and forth in the medium.

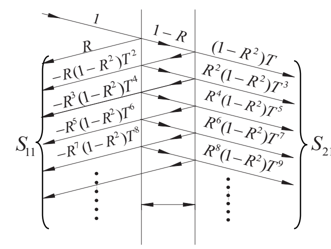


Figure 1: The electromagnetic wave reflection and transmission in medium.

Supposing that the reflection coefficient of the air-medium interface (A) is R, reflection coefficient of the medium-air interface (B) is $-R$ and the transmission coefficient of the medium is T with the length of L, the complex number S_{11} of reflection sum in the A interface and S_{21} of transmission sum in the B interface will be

$$\begin{cases} S_{11} = \dfrac{(1-T^2)R}{1-R^2T^2} \\ S_{21} = \dfrac{T(1-R^2)}{1-R^2T^2} \end{cases}, \quad (R \prec 1, T \prec 1) \cdot \tag{1}$$

Hence R and T can be solved from S_{11} and S_{21}. In addition, T and R relate to the complex dielectric constant ($\varepsilon_r = \varepsilon_r{}' - \varepsilon_r{}'' i$) and permeability ($\mu_r = \mu_r{}' - \mu_r{}'' i$) of the medium by:

$$\begin{cases} T = e^{-\gamma L}, \quad \gamma = i\omega/c\sqrt{\varepsilon_r\mu_r - \lambda_0/\lambda_c} \\ R = \dfrac{\sqrt{1-\lambda_0/\lambda_c} - \dfrac{1}{\mu_r}\sqrt{\varepsilon_r\mu_r - \lambda_0/\lambda_c}}{\sqrt{1-\lambda_0/\lambda_c} + \dfrac{1}{\mu_r}\sqrt{\varepsilon_r\mu_r - \lambda_0/\lambda_c}} \end{cases}, \tag{2}$$

where $\omega = 2\pi f$ is the circular frequency, c is the velocity of light, $\lambda_0 = c/f = c\omega/2\pi$ is the wavelength in free space, λ_c is the cut-off wavelength, and L is the length of the sample. Finally μ_r and ε_r could be solved through

$$\begin{cases} \mu_r = \dfrac{1+R}{\Lambda(1-R)\sqrt{\dfrac{1}{\lambda_0^2}-\dfrac{1}{\lambda_c^2}}}, & \dfrac{1}{\Lambda^2}=\dfrac{\varepsilon_r\mu_r}{\lambda_0^2}-\dfrac{1}{\lambda_c^2}=-\left[\dfrac{1}{2\pi L}\ln\left(\dfrac{1}{T}\right)\right]^2 \\ \varepsilon_r = \dfrac{\left(\dfrac{1}{\Lambda^2}+\dfrac{1}{\lambda_c^2}\right)\lambda_0^2}{\mu_r} & \operatorname{Re}\left(\dfrac{1}{\Lambda}\right)=\dfrac{1}{\lambda_g} \end{cases}. \quad (3)$$

During the test, the sample is installed inside the coaxial fixture as in Fig. 2 and the fixture is connected to a VNA (Vector Network Analyzer) through coaxial cables. Previous calculation theory requires S values at the head and end faces of the sample, while the measurement can only get the S values at the fixture calibration plane of A_1 and B_1. The fixture de-embedding has to be performed to transform the S values. Considering the fixture as a section of lossless coaxial line, measurement results of $S_{11}{}'$, $S_{21}{}'$ can be converted into S_{11}, S_{21} of the sample faces:

$$\begin{cases} S_{11} = S_{11}' \exp\left(i4\pi f d_1/c\right) \\ S_{21} = S_{11}' \exp\left(i4\pi f (L_f - L)/c\right) \end{cases}, \quad (4)$$

where f is the frequency of measurement, $\beta_0 = 2\pi f/c$ is the wave number and L_f is total length of the fixture with $L_f = d_1 + L + d_2$.

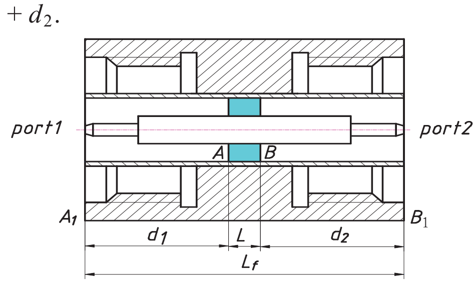


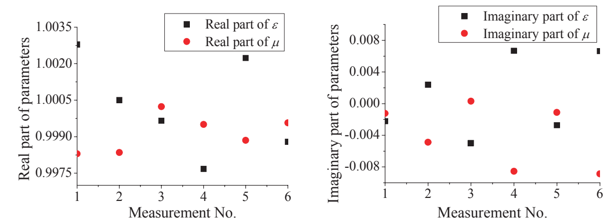
Figure 2: Assembling illustration of coaxial sample and fixture.

MEASUREMENT OF COMMON MEDIUMS

Measurement fixture is designed with the effective length of 80 mm, inner diameter of 3.04 mm and outer diameter of 7.00 mm, resulting in intrinsic impedance of 50 Ω. After the system constructed, the materials with specific electromagnetic parameters should be employed to validate the method and the system.

Test of the Hollow Fixture

The electromagnetic characteristics of air are simple and steady; therefore they are measured to test the hollow fixture. The dielectric constant and permeability of the air should be 1.00059-0i and 1.0000-0i respectively with the environment temperature of 25.0 ℃ and humidity of 30%. Six measurements at the LINAC operation frequency of 2856 MHz generate the calculation results as shown in Fig. 3. The arithmetic averages of ε = 1.0003+0.0010i and μ = 0.9991-0.0041i are accurately identical with the theoretical values.



(a) (b)

Figure 3: Test results of the electromagnetic parameters of air. (a) Real parts; (b) imaginary parts.

Test of PTFE Samples

Further validation is performed by dint of two PTFE rings, of which the electromagnetic parameters are ε = 2.04-0.0005i and μ = 1.00-0.00i in a broad band. One of the samples is 3.15 mm of inner diameter, 6.95 mm of outer diameter and 5.0 mm of length. The other is 3.12 mm of inner diameter, 6.92 mm of outer diameter and 15.0 mm of length. The experimental results of electromagnetic parameters come to ε_1 = 1.8933-0.0132i, μ_1 = 1.0212-0.0111i and ε_2 = 1.9121-0.0046i, μ_2 = 1.0098-0.0020i respectively. The parameters represent deviation from the theoretical values. The phenomenon is considered to be caused by the air gap between the samples and the fixture. Models of the two PTFE samples were created in CST and simulated. The simulations demonstrate that the parameters would be: ε_1 = 1.930-0.0061i, μ_1 = 1.000-0.0005i and ε_2 = 1.948-0.0014i, μ_2 = 0.998-0.0005i. It is clear that the air gap indeed makes both the dielectric constant and the permeability deviate from the theoretical value.

Effect of the Air Gap

It is necessary to study the effect of the air gap on the measurement of the electromagnetic parameters of FeSiAl.

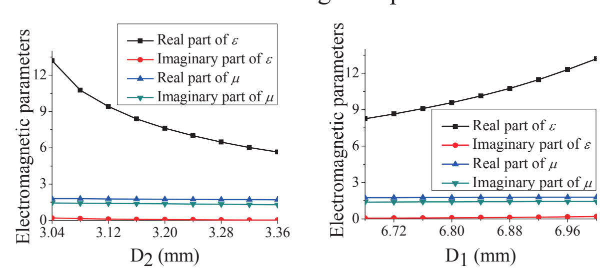


Figure 4: Influences of the inner diameter D_2 and outer diameter D_1 upon electromagnetic parameters.

A simulation in CST is employed to estimate the influence. According to the pre measured values of ε = 13.2-0.2i, μ = 1.8-1.44i, CST works out the S_{11} and S_{21} of the models with various D_1 and D_2 deviated. Then the dielectric constant and permeability could be calculated by previous formulas as shown in Fig. 4. It indicates that all the parameters of both real and imaginary parts decrease as the air gap enlarges. Moreover, the relative high value of dielectric constant brings about serious influence to the measurement.

MEASUREMENT OF THE ELECTROMAGNETIC PARAMETERS OF FeSiAl

The ring samples of FeSiAl are made by sinter-roasting method and can hardly prevent the air gap for their faulty appearances. A scheme of mixing the FeSiAl powder with paraffin to form a sample is proposed to eliminate the gap between the sample and the fixture.

Measurement of FeSiAl Mixed Samples

The density of the FeSiAl powder is ρ_m = 3.4 g/cm^3; the density of the used paraffin is ρ_i = 0.92 g/cm^3; the density of the mixed samples can be calculated from

$$\rho_{eff} = \frac{m}{V} = \frac{m}{\pi((D_1/2)^2 - (D_2/2)^2)L}, \tag{5}$$

where m is the weight of a sample and L is its length. Hence the volume ratio of FeSiAl powder in a sample is

$$h = \frac{\rho_{eff} - \rho_m}{\rho_i - \rho_m}. \tag{6}$$

Four samples with h of 0.3528, 0.4307, 0.5073 and 0.7276 are used in the experiments. The electromagnetic parameters at 2856MHz are measured as ε = 4.5264-0.0549i, 5.5580-0.0652i, 6.2544-0.1283i, 9.3636-0.1629i and μ = 1.3275-0.3884i, 1.3877-0.4961i, 1.4183-0.6048i, 1.4925-0.8834i, respectively. Meanwhile the paraffin is measured with dielectric constant of ε = 2.21-0.019i and permeability of μ = 1.02-0.019i.

Extraction of Electromagnetic Parameters of FeSiAl

Three common equivalent formulas of Bruggeman, Looyenga and QCACP are selected to extract the electromagnetic parameters from the data of the mixed samples for permeability:

$$h\frac{\mu_i - \mu_{eff}}{\mu_i + 2\mu_{eff}} + (1-h)\frac{\mu_m - \mu_{eff}}{\mu_m + 2\mu_{eff}} = 0, \tag{7}$$

$$(\mu_{eff})^{\frac{1}{3}} = h(\mu_i)^{\frac{1}{3}} + (1-h)(\mu_m)^{\frac{1}{3}}, \tag{8}$$

$$\mu_{eff} = \mu_m + \frac{3h\mu_{eff}(\mu_i - \mu_m)}{3\mu_{eff} + (1-h)(\mu_i - \mu_m)}. \tag{9}$$

In the above, μ_i is the permeability of FeSiAl, μ_m is the permeability of paraffin, μ_{eff} is the equivalent permeability of mixed medium, and h is the volume ratio of FeSiAl powder in the sample. According to the duality principle of electromagnetism, the same forms of formulas could be used for the dielectric constant. The calculation results of FeSiAl are presented in Fig. 5. It can be seen that different formulas give close values with different percentages of FeSiAl. The arithmetical averages of the dielectric constant and permeability from different formulas are listed in Table 1.

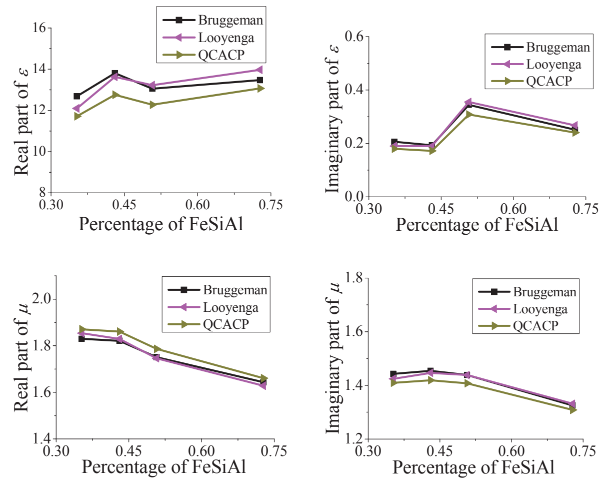


Figure 5: Electromagnetic parameters of FeSiAl through three equivalent formulas.

Table 1: Electromagnetic Parameters of FeSiAl

Equivalent Formulas	ε_i	μ_i
Bruggeman	13.26-0.25i	1.76-1.42i
Looyenga	13.23-0.25i	1.77-1.41i
QCACP	12.61-0.23i	1.79-1.39i

SUMMARY AND CONCLUSION

Coaxial transmission-reflection method is used to measure the electromagnetic parameters of a microwave-absorbing material of FeSiAl for LINAC collinear load R&D. The experiments of PTFE samples demonstrate that the air gaps between the samples and fixture lead to uncertainty of the results. CST simulations approve the phenomenon and revealed that the air gap would affect the measurement of FeSiAl seriously. A scheme of molding samples of the FeSiAl powder mixed with paraffin is proposed to solve the problem. Three equivalent formulas of mixed medium are employed and the dielectric constant and permeability of FeSiAl are obtained. Final results indicate that the samples with different volume ratio lead to consistent values of electromagnetism by all the equivalent formulas.

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