

Electromagnetic interference shielding effectiveness of Al/SiC composite foams

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Abstract Closed cell aluminum foams are fabricated by using the casting method. The electromagnetic interference (EMI) shielding effectiveness of foams are investigated in the frequency range of 1.44–5 and 8–12 GHz (X band). The shielding materials are made of Al foam with the addition of different concentrations of SiC (5, 10, 15 wt%). Results show that the Al/SiC composite foams have good shielding effectiveness. EMI shielding effectiveness of samples generally increased with increasing porosity and with the increasing of SiC content. The sample with 15 wt% SiC had shielding effectiveness values of up to 150 dB.

1 Introduction

With advance in electronic information and communication technologies, the problem of device malfunction caused by unwanted electromagnetic waves has been gaining importance. EMI is the performance degradation of a device due to electromagnetic disturbance, which can be a noise, an unwanted signal, or a change in the propagation medium. These problems are solved by electromagnetic shielding [1, 2]. EMI shielding and microwave attenuation materials are receiving immense interest to protect electronics, instrumentation and environment in commercial,

industrial, health care and defense applications [3]. Metals have limitations as electromagnetic wave absorbers, since their shallow skin depth makes them EMI shielding materials, mainly through surface reflection [4].

The recent new progress in the innovative metal foams in electromagnetic environment will hopefully lead the development of the new shielding applications [5]. Metal foams show a cellular structure consisting in a solid and a gaseous phase [6]. Cellular metallic materials are finding an expanding range of applications. Whether a suitable porous metal or metal foam can be found to solve a given problem depends on many conditions [7]. Over the past years, low cost Al foams have been produced for a wide range of potential applications such as the cores of sandwich panels, mechanical damping, energy absorption, acoustic absorption, and electromagnetic shielding [8, 9]. However, the problems of low strength and viscosity of Al matrix still limit their further utilization. For improving the viscosity and the matrix strength, various reinforcements were used, such as TiB₂, Y₂O₃, Al₂O₃, and especially SiC [10]. SiC is a group IV polar semiconductor with a wide band gap, and has many applications in electromagnetic wave absorption [11, 12].

In this study, Al foams are fabricated by casting method, and the effects of porosity and SiC additive on the EMI shielding effectiveness of Al foams are investigated.

2 Experimental procedure

2.1 Production of foam

In this study, closed cell Al foams were manufactured in Academic Center for Education, Culture and Research (ACECR) of Mashhad by using the casting method. Al casting alloy LM13 with high casting ability was used to

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produce the foam. Al melt was heated in a graphite crucible up to 700 °C. The SiC powder was added to the Al melt to raise viscosity. The melt was then stirred with a steel mixer at speed of 1000 rpm for 20 min. The melt was transferred to a preheated mold to 700 °C. CaCO₃ was added to the melt for the foam production; and the melt was stirred at 1400 rpm for 1 min. Subsequently, the melt was held in the furnace until a cellular structure was formed; then it was removed from the furnace. The characteristics of produced foam samples are listed in Table 1.

2.2 Measurement of the shielding effectiveness

The electromagnetic wave transmits via a sender and an antenna to the surface of the tested sample, and behind the sample, the other antenna receives the transmitting signal.

The measurement of EMI shielding effectiveness performed with a network analyzer HP8720C and two broadband antenna SAS571 (transmitting and receiving antenna). The schematic of EMI shielding measurement setup is shown in Fig. 1. The dimension of the tested samples is 19 cm × 19 cm × 19 mm.

3 Results and discussion

3.1 Shielding effectiveness

3.1.1 Mechanisms of shielding

There are several methods for protection from electromagnetic interference. The electromagnetic shielding is one of the effective methods. The electromagnetic shield effect is described by the following equations:

$$SE = -20 \log \frac{|E|}{|E_0|} [\text{dB}] (\text{electric shield}) \tag{1}$$

$$SE = -20 \log \frac{|H|}{|H_0|} [\text{dB}] (\text{magnetic shield}) \tag{2}$$

where E_0 is the electric field at the observation point in the absence of the shield and E is the one in the presence of the shield. H and H_0 are the magnetic field at the observation

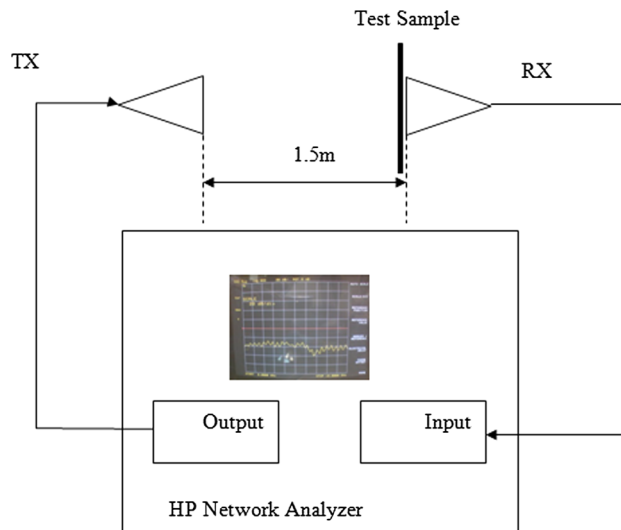


Fig. 1 Schematic diagram of EMI shielding test setup

point with and without the shield. As the electromagnetic shielding theory, the one by Schelkunoff is renowned and has been applied to the shielding problems of various shapes and is considered as a guideline [13].

In accordance with Schelkunoff transmission lines theory, the shielding effectiveness of a material is derived from three parts [14]. The first one is the reflection by the two interfaces (air-foam and foam-air), called reflection loss and indicated as R . The second one is the attenuation of the transmitted wave, called absorption loss and indicated as A . The third contribution is given by the multiple reflection effect, called multiple reflection loss and indicated as M [15]. Therefore, EMI shielding effectiveness for a homogeneous and single layer electromagnetic shield material can be written as:

$$SE = R + A + M [\text{dB}] \tag{3}$$

But the aluminum foam structure cannot be treated as the solid material. The detailed transmission analysis is necessary. Schematic diagram of electromagnetic wave transmission in aluminum foam is shown in Fig. 2 [16].

The primary mechanism of EMI shielding is reflection of the radiation by the shield, the shield must have mobile charge carriers (electrons or holes) which interact with the electromagnetic fields in the radiation. Therefore, the shield tends to be electrically conducting. Metals are the most common materials for EMI shielding. They function mainly by reflection caused by the free electrons [17]. The reflection coefficient between free space and aluminum is close to one because of the large impedance differences between them, due to the fact that the charged particles (free electrons and holes) interact with the electromagnetic field in Al foams. So the reflection has a dominant role in EMI shielding of Al foams [16]. The second mechanism of

Table 1 Characteristics of foam samples

Sample	Porosity (%)	SiC
S1	85	5
S2	83	5
S3	83	10
S4	78	10
S5	82	15
S6	77	15

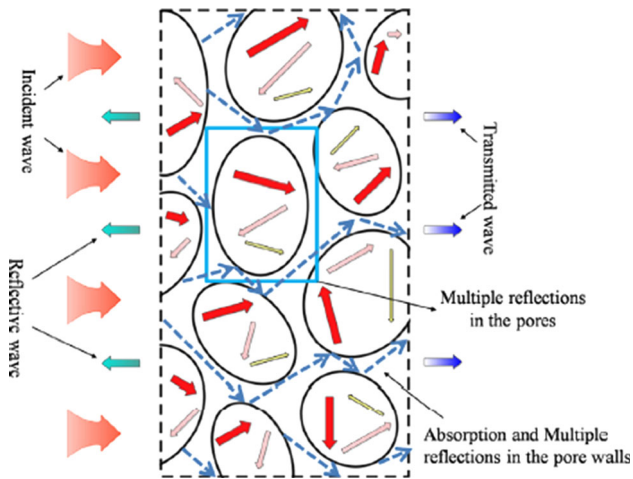


Fig. 2 Schematic diagram of electromagnetic wave transmission in Al foam [16]

EMI shielding is absorption. For significant absorption of radiation by the shield, the shield must have electric or magnetic dipoles that interact with the electromagnetic fields in the radiation [18]. Absorption is related to the permeability, electrical conductivity, electromagnetic wave frequency and shield thickness [16]. The absorption loss is a function of $\sigma_r \mu_r$, whereas the reflection loss is a function of $\frac{\sigma_r}{\mu_r}$, that σ_r is the electrical conductivity relative to copper and μ_r is the relative magnetic permeability. Aluminum, gold, silver and copper are excellent for reflection, because of their high conductivity [17]. In addition to the reflection and absorption, a mechanism of shielding is multiple reflections, that refer to the reflections at various surfaces or interfaces in the shield. This mechanism requires the presence of a large surface area (a porous or foam material) or interface area (a composite material containing a filler) in the shield [17]. When the distance between the reflecting surfaces or interfaces is large compared to the skin depth, the multiple reflections loss can be neglected. Electromagnetic radiation at high frequencies permeates only the near surface region of an electrical conductor, that it is known as the skin effect [17].

The depth where the field drops to e^{-1} of the incident value is called the skin depth, which is given by [19, 20]:

$$\delta = \frac{1}{\sqrt{\pi \mu \sigma f}} \quad (4)$$

where f = frequency, μ = magnetic permeability = $\mu_o \mu_r$, μ_r = relative magnetic permeability, $\mu_o = 4\pi \times 10^{-7}$ Hm⁻¹, and σ = electrical conductivity in Ω^{-1} m⁻¹.

Therefore, the skin depth decreases with increasing frequency and conductivity.

Xu and Hao [16] expressed that the electromagnetic wave transmission in the Al foams is much more complex

than that in the solid metal. They modified Eq. (3) to following equation for Al foams:

$$SE = R + A + M_W + M_P + W + E + O \quad (5)$$

where R is the reflection loss at the first interface, A is the absorption loss in the pore walls, M_W is the multiple reflections in the pore walls, M_P is the multiple reflections in the pores, W is fluctuation factor due to wave-current interaction, E is the eddy-current loss, and O is fluctuation factor due to microstructure defects.

The eddy-current loss is another important shielding form that has relationship with structure and electrical properties of the shielding material. Al foam pore can be treated as a typical spherical shell shield, and the EMI shielding effectiveness at high frequencies can be approximated as [16]:

$$SE = -20 \log \frac{3\sqrt{2}\delta}{re^{\frac{d}{\delta}}} \quad (6)$$

where r is radius of spherical shell, d is the spherical shell thickness, and δ is skin depth. So with a thicker wall, greater radius, and higher frequency, the higher eddy-current loss is achieved [16].

3.1.2 Effect of porosity

Figures 3, 4 and 5 show EMI shielding effectiveness curves of Al foams containing the same SiC content with different porosity within the wave frequency of 1.44–5 GHz.

According to Fig. 3, the shielding effectiveness values of foams are increased with increasing porosity. The sample with the highest porosity (S1) has best shielding effectiveness values (up to 160 dB) amongst other samples. In accord with Figs. 4 and 5, the shielding effectiveness

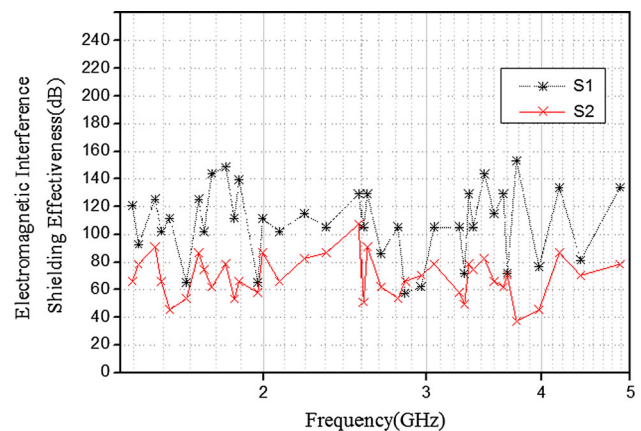


Fig. 3 EMI shielding effectiveness curves of Al foams with 5 wt% SiC as a function of porosity and frequency

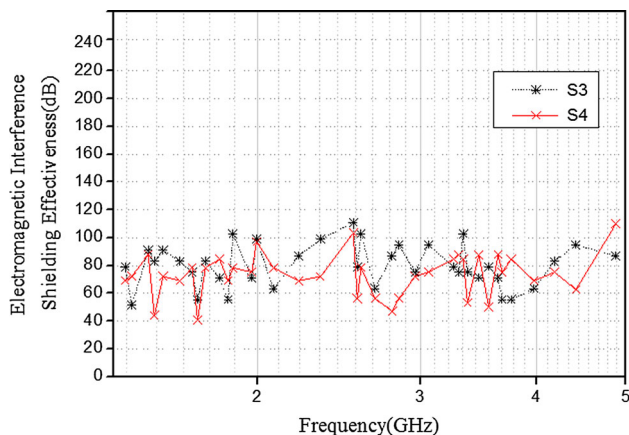


Fig. 4 EMI shielding effectiveness curves of Al foams with 10 wt% SiC as a function of porosity and frequency

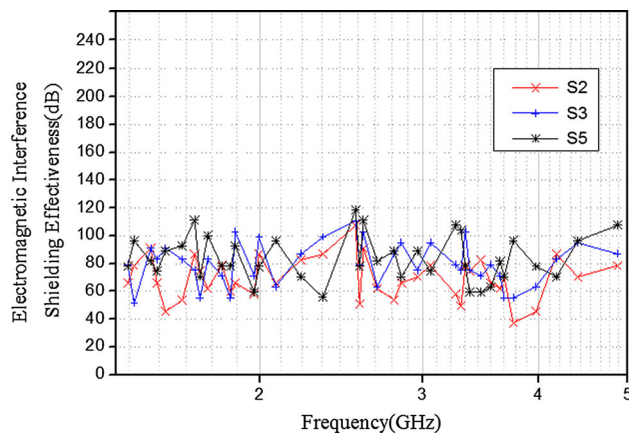


Fig. 6 EMI shielding effectiveness curves of Al foams as a function of SiC contents and frequency

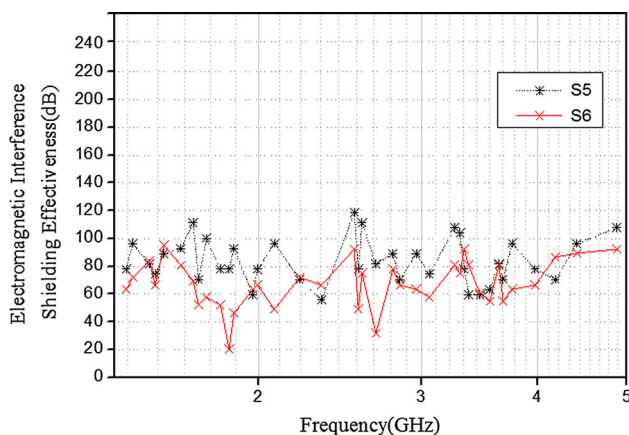


Fig. 5 EMI shielding effectiveness curves of Al foams with 15 wt% SiC as a function of porosity and frequency

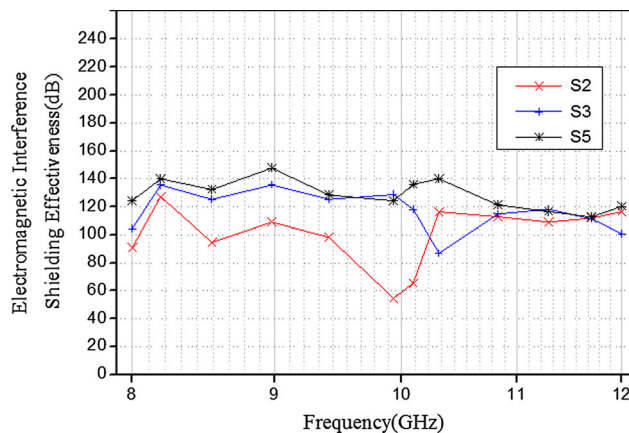


Fig. 7 EMI shielding effectiveness curves of Al foams in X band

values of samples are close. It shows that the effect of porosity decreases with increasing concentration of SiC additive. We can say, generally EMI shielding effectiveness increases with increasing the porosity.

3.1.3 Effect of SiC additive

Figure 6 shows EMI shielding effectiveness curves of Al foams with different SiC content and the same porosity within the wave frequency of 1.44–5 GHz.

According to Fig. 6, we can say, almost the SiC additive concentration improves the EMI shielding effectiveness of Al foams. It seems to us that the effect of SiC content is more at high frequencies. In order to verify this, the shielding properties of samples were measured in the frequency range of 8–12 GHz (X band). EMI shielding effectiveness curves of Al foams with different SiC content and the same porosity in X band are shown in Fig. 7.

According to Fig. 7, obviously the shielding effectiveness of foams is enhanced with increasing SiC content. Thus, the SiC additive shows its effect at high frequencies. The sample with the highest additive content (15 wt% SiC) shows the shielding effectiveness up to 150 dB. The EMI shielding effectiveness values of the Al/SiC composite foams at the frequency of 9 GHz are plotted against the SiC content in Fig. 8.

These results show that the SiC additive concentration plays an important role in enhancing the shielding effectiveness of Al foams at high frequencies. SiC has good physical and electrical properties and is used in many electronic applications at high voltage and high frequencies. The density of foam increases with increasing SiC content. So the improvement of shielding effectiveness with increasing SiC content may be caused by increasing conductivity. The reinforcement in EMI shielding effectiveness is mainly ascribed to the improvement of conductivity or the decrease in electrical resistivity. Although, conductivity is not a scientific criterion for EMI shielding;

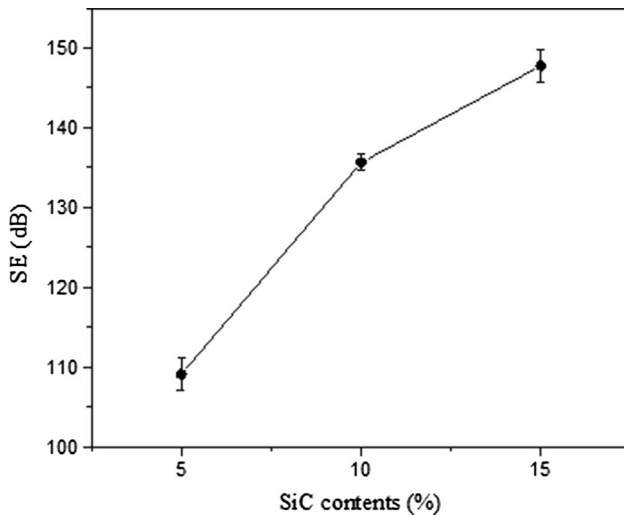


Fig. 8 Effect of SiC additive concentration on shielding effectiveness of foams (S2, S3, S5) at 9 GHz

but higher electrical conductivity causes higher EMI shielding effectiveness due to reflection [21].

The SE_R and SE_A are associated with the electrical conductivity to the following equations [22, 23]:

$$SE_R = 39.5 + 10 \log \frac{\sigma}{2\pi f \mu} \quad (7)$$

$$SE_A = 8.7d \sqrt{\pi f \mu \sigma} \quad (8)$$

Where σ is the electrical conductivity, f is the frequency, μ is the permeability, and d is the thickness. Obviously, both SE_R and SE_A increase with the increase of σ .

The foam is created by an aluminum cluster: the randomly distributed gas pores with various sizes in the metallic matrix. If the cluster does not exist, the foam disintegrates and effective properties are zero [24].

The effective property can be expressed as [25]:

$$\pi \propto (P - P_C)^t \quad (9)$$

where π is the effective property, P is the volume fraction of the relevant component, and t is a constant that often called the critical exponent.

Therefore, π becomes zero at the percolation threshold P_C and near P_C it behaves as a power of $P - P_C$.

If the foam structure is considered, the threshold can be fixed at zero density ($P_C = 0$) and then Eq. (9) can be expressed as [24]:

$$\frac{\lambda}{\lambda_S} = K \left(\frac{\rho}{\rho_S} \right)^t \quad (10)$$

where λ and λ_S are the electrical conductivity of foam and solid, ρ is the density of foam, ρ_S is the density of solid of which it is made and K is a constant.

While the relative density decreases, the average cross section available for conduction decreases and the

tortuosity of the current path increases, therefore the resistivity increases [24].

An interesting result were obtained in this work, in which the pore size increases with the increasing of SiC content, as shown in Fig. 9. SEM images and EDS analysis of samples are also shown in Fig. 10.

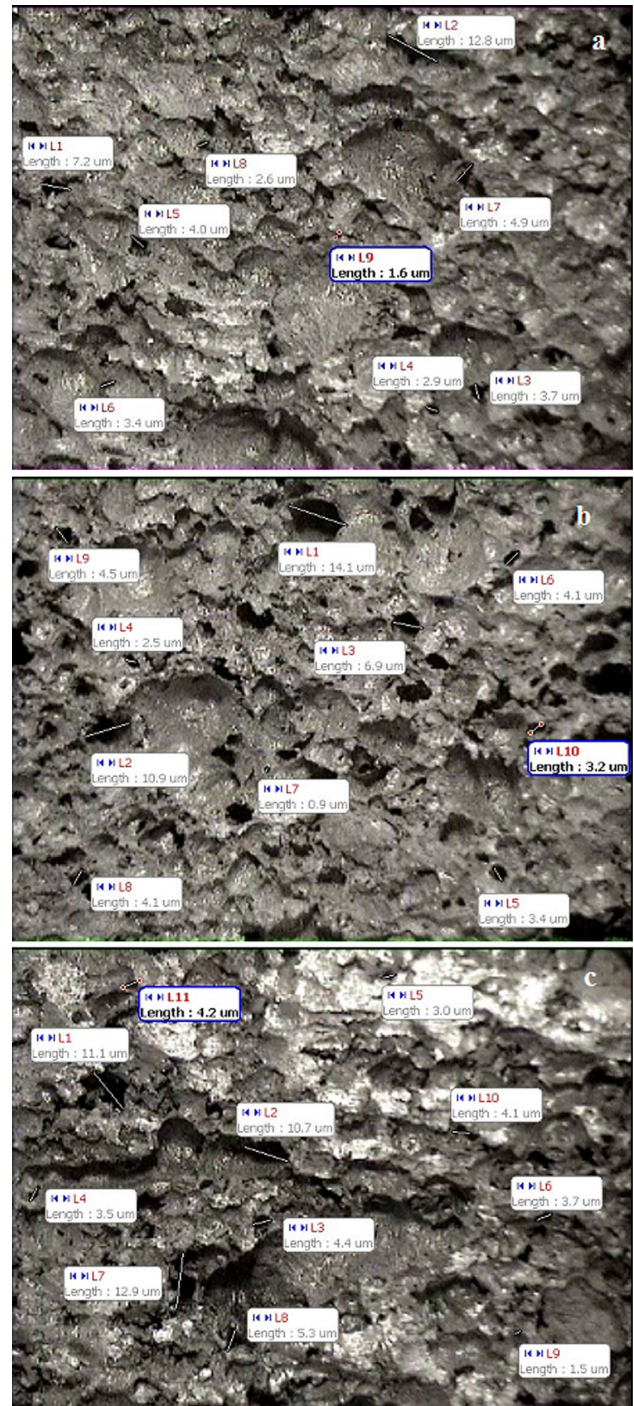


Fig. 9 Images of foams: **a** S2 (5 wt% SiC), **b** S3 (10 wt% SiC), and **c** S5 (15 wt% SiC)

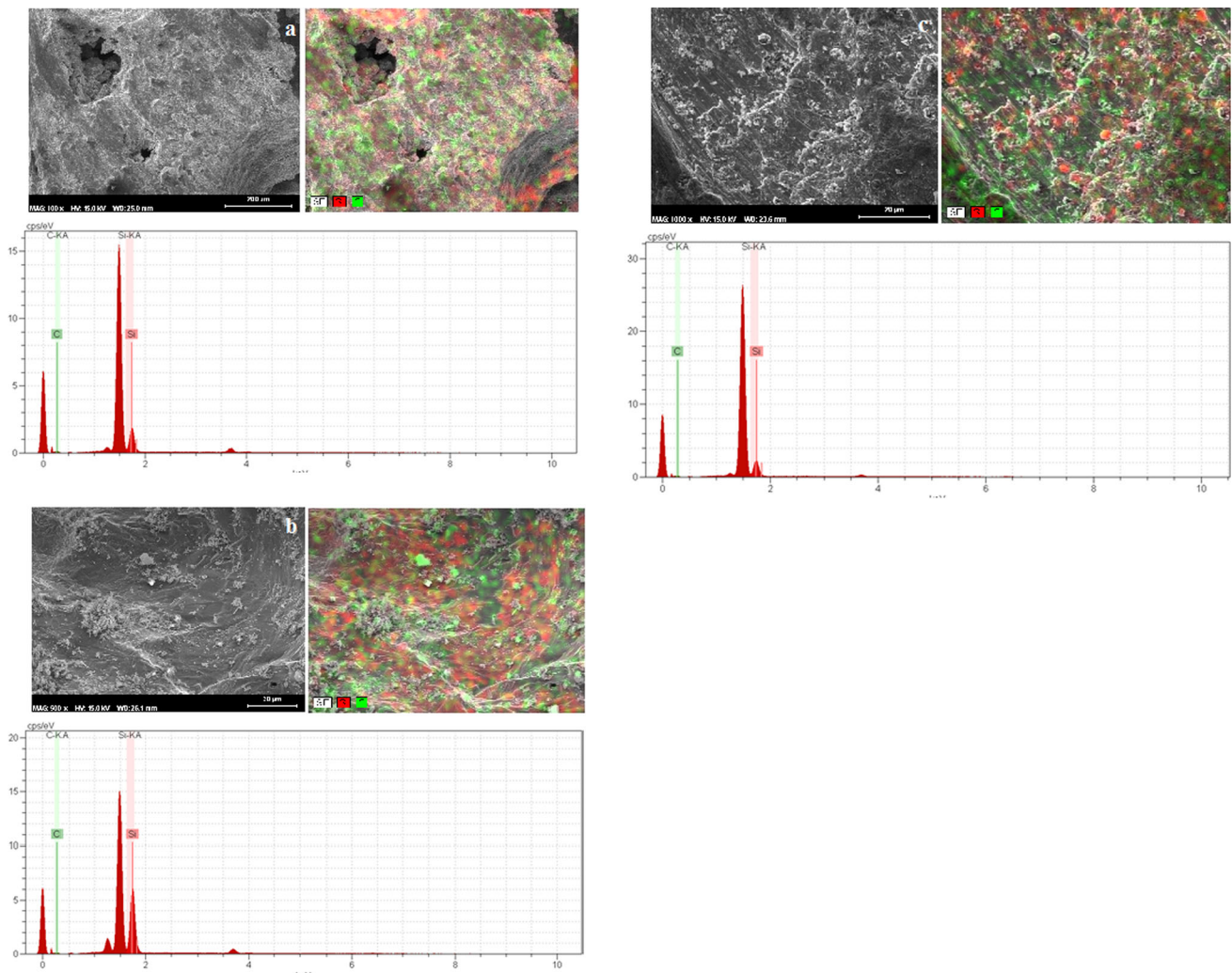


Fig. 10 SEM images and EDS analysis of foams: **a** S2 (5 wt% SiC), **b** S3 (10 wt% SiC), and **c** S5 (15 wt% SiC)

Generally, the EMI shielding effectiveness of Al foam mostly determines by the reflection loss and the multiple reflections in the pores, and the absorption and the eddy-current loss play important roles at high frequencies [16]. The increase of pore size can lead to the increase of the eddy-current loss and consequently the improvement of shielding effectiveness at high frequencies, as shown in Fig. 7.

Figure 10 shows the existence of Si and C elements in the pore walls. The thickness of pore walls increases with the increasing of SiC content; therefore, the eddy-current loss and the absorption loss increase and lead to the improvement of shielding effectiveness.

3.1.4 Effect of thickness

The sample thickness affects the shielding effectiveness. The absorption and the multiple reflections are associated

with the sample thickness according to the following equations [13, 19]:

$$A = 20 \log \left(\exp \left(\frac{-t}{\delta} \right) \right) \quad (11)$$

$$M = 20 \log \left(1 - \exp \left(\frac{-2t}{\delta} \right) \right) \quad (12)$$

where t is the thickness of the electromagnetic shield material.

In the present study, thick samples may be related to the high values of shielding effectiveness of all foams.

4 Conclusion

The result of the shielding of samples containing the same SiC content with different porosity within the frequency range of 1.44–5 GHz showed that the shielding

effectiveness of foam were increased with increasing porosity; and the sample with the highest porosity showed the shielding effectiveness up to 160 dB. The results of the shielding of samples with different SiC content and the same porosity in the frequency range of 1.44–5 and 8–12 GHz showed that the increasing SiC content can lead to the increase of conductivity and the increase of reflection loss. The increase of SiC content can also lead to the increase of the pore size and the increase of the thickness of pore walls; therefore, the eddy-current loss and the absorption loss increase. All these lead to the improvement of shielding effectiveness. The sample with 15 wt% SiC showed the shielding effectiveness values between 115 and 150 dB in the frequency range of 8–12 GHz (X band). These results indicate that the SiC additive plays an important role in improving the shielding effectiveness of Al foams at high frequencies.

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