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Feasibility Study of Porous Aluminum for Electromagnetic Shielding Applications

Ling Yong

School of Electrical and Electronic Engineering

A thesis submitted to the Nanyang Technological University
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Master of Engineering

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Abstract

For a very long time, people have noticed that natively existing porous materials have higher stiffness and low specific weight. This has prompted the development of artificial cellular material made from metals, which leads to different porous metals being produced recently. Porous metals have been used widely in construction, aerospace and automobile industries for their light-weight and reasonable mechanical properties. However, very little research work has been carried out to explore the feasibility of extending porous metals in electromagnetic shielding applications.

For architectural electromagnetic shielding, either welded solid metal pieces or modular sandwiched steel-wood-steel panels are adopted for their proven excellent shielding performance. However, they are heavy and can pose loading problems to existing buildings. The porous metal offers a possible solution to such as problem due to its light-weight nature. However, its electromagnetic shielding behaviors and mechanical properties have not been investigated.

In this thesis, the feasibility of using porous metals for electromagnetic shielding is studied. It has been shown that porous Aluminum can be a promising ultra light-weight material with reasonable ruggedness for architectural shielding purposes.

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List of Abbreviations and Symbols

SE	Shielding Effectiveness
EMI	Electromagnetic Interference
IFAM	Fraunhofer Institute for Manufacturing and Advanced Materials
TALAT	Training in Aluminum Application Technologies
IEEE	Institute of Electrical and Electronics Engineering
ASTM	American Society for Testing and Materials
STD	Standard
TEM Wave	Transverse Electromagnetic Wave
TDR	Time Domain Reflectometer
EM	Electromagnetic
RF	Radio Frequency
σ	Electrical Conductivity
δ	Skin Depth of Porous Material
F	Frequency of EM Wave
μ	Permeability of Porous Material
Z_w	Characteristic Impedance of Air
Z_s	Characteristic Impedance of Porous Material

Chapter 1 Introduction

1.1 Motivation

With the rapid advancement in wireless communication technologies and portable electronic devices, electromagnetic interference (EMI) has become a critical design issues that affects the quality of our daily lives. Undesired electromagnetic (EM) waves may interfere with sensitive electronic devices as well as causing radiation hazards to human bodies. Hence, EM shielding has chosen as one of the solutions to eliminate EMI problem. Conventional methods for architectural shielding use either welded solid metal pieces or modular sandwiched steel-wood-steel panels. The welded solid metallic shielded enclosure provides excellent shielding performance but requires special welding skills and therefore, can be very expensive to implement. The modular sandwiched-panel shielded enclosure can be easily installed but the overall shielding effectiveness (SE) is always limited by the electromagnetic field leakage through the panel joints. Nevertheless, these two methods have one thing in common; they are heavy and difficult to handle with during the installation process.

In the past decade, the interest in porous metals, also commonly known as metallic foams, has increased considerably. The main reason for this development is its light weight and reasonable mechanically properties that are required by the automotive and aerospace industries. Porous metals, particularly Aluminum, offer a great potential for many engineering applications, where weight is a major concern, particularly in the construction, automotive and aerospace industries. Besides its light-weight property, the porous Aluminum also has other interesting features, such as incombustibility and sound absorption ability. The motivation of this research project is to investigate the feasibility of using porous Aluminum as an alternative material for architectural electromagnetic shielding purposes. Due to its light-weight property, porous Aluminum panels could be added to existing building without the concern of additional loading that may pose potential structural loading problem, which makes it an attractive shielding alternative.

1.2 Electromagnetic Compatibility

1.2.1 Overview of Electromagnetic Interference

Electromagnetic Interference (EMI) is a phenomenon that electronic devices or systems generate electromagnetic field that degrades or limits the satisfactory operation of other electronic devices or systems in its vicinity [1]. EMI and its mitigation arose with the first spark-gap experiment of Marconi in the late 1800s. By that time, the main EM wave source was the radio antennas and the interference problem could be simply resolved. However, technical papers on radio interference began to appear in various technical journals around 1920. Early radio receivers and antennas are not well-designed and can be easily interfered by external noise sources and electrical apparatus such as electric motors and electric railways. These problems were later resolved with better design technology at that time. More EMI problems surfaced again during World War II due to the use of electronic devices, primarily radios, navigation devices, and radar on military aircraft and ships. Instances of interference between radios and navigational devices on aircraft were frequently reported. After World War II, the invention of bipolar transistors led to the development of integrated circuits and microprocessor chips. These digital devices, when mounted on poorly designed printed circuit board (PCB) resulted in significant increase in interference problems. It was by that time, the electromagnetic compatibility (EMC) issue was brought to the forefront. Nowadays, due to heavy usage of digital devices and wireless communication tools in our daily lives, EMI can be a severe problem, if there are no regulatory controls by the government agencies.

There are many reported EMI incidents and some of them are highlighted here to illustrate possible serious consequences.

A new version of an automobile had a microprocessor-controlled emission and fuel monitoring system installed. A dealer received a complaint that when the customer drove down a certain street in the town, the car would stall. Measurement of the ambient fields on the street revealed the presence of an illegal FM radio transmitter. The signals from that transmitter coupled onto the wires leading to the processor and caused it to

shut down [2].

In 1982 the United Kingdom lost a destroyer, the HMS Sheffield, to an Exocet missile during an engagement with Argentinean forces in the battle of the Falkland Islands. The destroyer's radio system for communicating with the United Kingdom would not operate properly while the ship's antimissile detection system was being operated due to interference between the two systems. To temporarily prevent interference during a period of communication with the United Kingdom, the antimissile system was turned off. Unfortunately, this coincided with the enemy launch of the Exocet missile [2].

These are just a few of the many instances of EMI in our dense electronic world. The consequence of an EMI incident can be life threatening sometimes. Hence, it is rather clear that solutions are needed to counter EMI problems.

1.2.2 Electromagnetic Compatibility

Electromagnetic Compatibility (EMC) is defined as the capability of electrical and electronic systems, equipment, and devices to operate in their intended electromagnetic environment within a defined margin of safety and at design levels or performance without suffering or causing unacceptable degradation as a result of electromagnetic interference [3]. A system is electromagnetically compatible with its environment if it satisfies the following three criteria:

1. It does not cause interference with other systems.
2. It is not susceptible to emissions from other systems.
3. It does not cause interference with itself.

EMC is concerned with the generation, transmission, and reception of electromagnetic energy. These are the three basic aspects of the EMC problem that form the basic framework of any EMC design, as illustrated in Figure 1.1.

Figure 1.1 Basic Aspects of EMC Problem [2]

A source (also referred to as an emitter) produces the emission, and a transfer or coupling path transfers the emission energy to a receptor (receiver), where it is processed, resulting in either desired or undesired behavior. Interference occurs if the received energy causes the receptor to behave in an undesired manner. Hence, in EMC engineering, we suggest three ways to prevent interference:

1. Suppress the emission at its source.
2. Make the coupling path as inefficient as possible.
3. Make the receptor less susceptible to the emission.

The transfer of EM energy can be further broke into four sub-groups [2-3], as shown in Figure 1.2.

Figure 1.2 Four basic EMC sub-problems: (a) radiated emissions; (b) radiated susceptibility; (c) conducted emissions; (d) conducted susceptibility [2]

In the above figure, radiated emissions are the component of RF energy that is emitted through a medium as an EM field and radiated susceptibility is a product's relative ability to withstand EM energy that arrives via free space propagation. Whereas the conducted emissions are the component of RF energy that is emitted through a medium as a propagating wave generally through a wire or interconnect cables and the conducted susceptibility is a product's relative ability to withstand EM energy that penetrates through external cables, power cords, and input-output (I/O) interconnects. These problems lie with the design of electronic systems hence are of most importance. However, there are also other EMC aspects worth mentioning, for examples, electrostatic discharge (ESD), electromagnetic pulse (EMP), lightning and secure communication and data processing (TEMPEST), as shown in Figure 1.3.

Figure 1.3 Other aspects of EMC: (a) ESD; (b) EMP; (c) lightning; (d) TEMPEST (secure communication and data processing) [2]

1.2.3 Electrical Dimensions

One of the most important parameters in electromagnetic (EM) wave is the electrical dimension, it is measured expressed in terms of wavelengths. A wavelength is the distance that a single-frequency, sinusoidal electromagnetic wave travels when its phase is changed by 360° . The EM wave travels at the speed of:

$$v = \frac{1}{\sqrt{\mu\epsilon}} \text{ m/S} \quad (1.1)$$

Where $\mu = \mu_r\mu_o$ H/m and $\epsilon = \epsilon_r\epsilon_o$ F/m are the permeability and the permittivity of the medium where the EM wave travels, respectively. In free space, μ_r and ϵ_r are both equal to 1, so:

$$v = \frac{1}{\sqrt{\mu\epsilon}} = 3 \times 10^8 \text{ m/s}$$

The wavelength of an EM wave is:

$$\lambda = \frac{v}{f} \text{ m} \quad (1.2)$$

Where v is the propagation speed of EM wave in m/S and f is the frequency of EM wave in Hz.

1.3 Electromagnetic Shielding

Electromagnetic (EM) shielding is a material barrier that restricts the propagation of electromagnetic wave between two regions. This kind of barrier is usually made of conductive material. There are two major applications for EM shielding, to protect sensitive electronic devices from EMI as well as to shield the noisy devices so that they do not emit excessive electromagnetic emission, as shown in Figure 1.4.

Figure 1.4 Use of a Shielded Enclosure, (a) to contain radiated emissions and (b) to exclude radiated emissions; [2]

The amount of EM shielding depends very much upon the material used, its thickness, the size of the shielded volume and the frequency of the fields of interest and the size, shape and orientation of apertures in a shield to an incident electromagnetic field. Electrical conductivity and permeability of a material are the determining factors that affect the intrinsic shielding effectiveness of a material. Conventionally, there are mainly two methods to construct architectural shielding. One is to weld solid metal pieces together and the other is to join modular sandwiched steel-wood-steel panels with mechanical joining techniques.

Welded construction is usually consisting of continuous 1.897 mm (14 Gauge) thick steel plate and angles to form the enclosure. Thicker material may be used if it is more cost-effective or required for structural reasons. Welded construction is used when a shielded facility requires a long maintainable service life of high-level shielding protection, such as 100 dB attenuation [4-7].

Paneled construction is usually associated with a lower level (50 to 70 dB) of shielding effectiveness. This construction will usually consist of modular panels bolted together with metal strips or channels. Panels are commonly plywood with steel sheets laminated to one or both sides. Paneled construction is used when a shielded facility's service life is short, 10 years or less, or the system is expected to be relocated. This kind of construction requires more maintenance than a welded construction [4-7].

For most practical applications, the attenuation of 99.9% to 99.99% of the incident electromagnetic wave is sufficient, which work out to be between 60 and 80 dB shielding effectiveness. In this kick off research project for the shielding effectiveness of porous aluminum, we are looking to achieve a shielding effectiveness of at least 60 dB for the frequency band of 250 MHz to 1 GHz.

To quantify the shielding performance of a shielded enclosure, the shielding effectiveness (SE) is a commonly used parameter to describe the reduction of electric (E) or magnetic (H) field offered by the shielding material. It is usually expressed in decibel (dB) as follows:

$$\begin{aligned} SE_{E\text{-field}} &= 20 \log \frac{E_i}{E_t} \quad \text{dB} \\ SE_{H\text{-field}} &= 20 \log \frac{H_i}{H_t} \quad \text{dB} \end{aligned} \quad (1.3)$$

Where $E_i(H_i)$ is the incident electric (magnetic) field strength and $E_t(H_t)$ is the transmitted electric (magnetic) field strength

The EM shielding mechanism has been well documented in many literatures and will only be discussed briefly here. In general, there are two major mechanisms that contribute to the shielding of metallic material, the absorption loss and the reflection loss. The absorption loss is due to attenuation of the EM field in the material when the EM wave propagates within the material and the reflection loss is due to impedance mismatch between boundaries of two different media where the EM wave passes through [1, 2]. Figure 1.5 illustrates the two mechanisms when the EM wave propagates through a conductive barrier.

Figure 1.5 Illustration of Shielding Effective of a Conductive Barrier [2]

1.3.1 Absorption Loss

For an EM wave propagates through a shielding material, the E and H fields within the material can be expressed as:

$$E(t) = E(0)e^{-\gamma} \quad (1.4)$$

$$H(t) = H(0)e^{-\gamma}$$

$$\gamma = \alpha + j\beta = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)} \quad (1.5)$$

Where γ is the propagation constant, β is the phase constant in radians per meter, α is the attenuation constant in Nepers/meter, μ is the permeability of the material in H/m, σ is the electrical conductivity of the material in S/m.

As good shielding material is predominantly conductive in nature ($\sigma \gg j\omega\epsilon$), the propagation constant can be simplified as:

$$\gamma = \sqrt{j\omega\mu\sigma} = (1 + j)\sqrt{\pi f\mu\sigma} \quad (1.6)$$

Therefore, the attenuation constant is given by:

$$\alpha = \sqrt{\pi f\mu\sigma} \quad (1.7)$$

The loss resulted by the attenuation of EM wave passing through the shield is called the absorption loss. For a material with thickness t in m, the absorption loss can be determined by:

$$A = 20 \log \frac{|E(0)|}{|E(t)|} = 20 \log \frac{|H(0)|}{|H(t)|} = 8.686 \left(\frac{t}{\delta} \right) \text{dB} \quad (1.8)$$

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \text{m}$$

Where δ is the skin depth of the material in meter, f is the frequency of the EM wave in Hz, μ is the permeability of the material in H/m and σ is the electrical conductivity of the material in S/m [1, 2].

1.3.2 Reflection Loss

The reflection mechanism can be explained by Figure 1.6.

Figure 1.6 Mechanism of Reflection Shielding Effectiveness [2]

In Figure 1.6(a), when EM wave arrives the left interface, the transmission coefficient is

calculated as:

$$\frac{E_l}{E_i} = \frac{2Z_s}{Z_w + Z_s} \quad (1.9)$$

Again, when EM wave arrive the right interface as shown in Figure 1.6(b), the transmission coefficient is calculated as:

$$\frac{E_t}{E_l} = \frac{2Z_w}{Z_w + Z_s} \quad (1.10)$$

Combining equations (1.9) and (1.10), we have the ratio of transmitted field and the incident field in the absence of attenuation:

$$\frac{E_t}{E_i} = \frac{E_l}{E_i} \times \frac{E_t}{E_l} = \frac{4Z_w Z_s}{(Z_w + Z_s)^2} \quad (1.11)$$

As the impedance of the barrier (Z_s) is much smaller than the wave impedance (Z_w), very little of the electric field is transmitted through the first (left) boundary. Hence, the calculation of reflection loss can be given as:

$$R = 20 \log \frac{|Z_w|}{4|Z_s|} \quad (1.12)$$

$$|Z_s| = \sqrt{\frac{2\pi f \mu}{\sigma}}$$

Where f is the frequency of the EM wave in Hz, μ is the permeability of the material in H/m, Z_w is the wave impedance in free space (377 Ω for far field source), Z_s is the impedance of the shielded barrier and σ is the electrical conductivity of the material in S/m [1, 2].

1.4 Organization of Thesis

This thesis is organized as follows:

Chapter 1 provides an overview of EMI/EMC, some theoretical background of electromagnetic shielding and the motivation of the thesis.

Chapter 2 presents a literature review of different fabrication methods of the porous Aluminum. Two major methods are described in details. Comparisons of the mechanical

properties of porous Aluminum with other commonly used construction materials, such as solid Aluminum, wood and concrete are presented.

Chapter 3 looks into the measurement techniques of shielding effectiveness of shield material. Two common standards to measure the shielding effectiveness of a material are explored. The design of test jig and necessary modification in the test procedure are also explained. The advantages and limitations of these two methods are also described.

Chapter 4 proposes a measurement method to estimate the electrical conductivity of porous Aluminum. A circuit for the measurement is designed and validated. With the proposed measurement method, the conductivity of porous Aluminum is measured. Based on the measured conductivity, shielding performance of porous Aluminum is evaluated.

Chapter 5 presents the measured and simulated shielding effectiveness results of porous Aluminum. Finally, a porous Aluminum shielded enclosure is assembled and its shielding performance is measured.

Chapter 6 concludes the project and recommends future work that worth exploring.

Chapter 2 Porous Aluminum

There are many different methods to fabricate the porous Aluminum blocks [12-17]. It is impossible to include all these methods and explain in details in this chapter. Therefore, only two commonly used methods are briefly described here, they are:

- i. Fabrication based on melted metal process
- ii. Fabrication based on metal powder mixing process

2.1 Fabrication methods for porous Aluminum

2.1.1 Fabrication based on melting metal process

2.1.1.1 Alcan/Norsk Hydro process

Figure 2.1 Alcan/norsk Hydro Process [12]

This process is illustrated in Figure 2.1. It obtains the Aluminum foam by injecting gases into the Aluminum melt before it solidifies. Usually, 10 to 15% of SiC or Al_2O_3 is added to the melt to increase its viscosity. A gas (air, nitrogen or argon) is then injected into the melt using a rotating impeller. The floating foam is continuously pulled off from the

surface of the melt. With this process, foam slabs of large size, for example, 10 m (length) $\times$ 1 m (width) $\times$ 0.1 (thickness) can be produced. This process can produce a porous sheet material with porosities ranging from 80 to 97%.

2.1.1.2 Alporas process

Figure 2.2 ALPORAS-Technologies [13]

This process is developed by Shinko Wire in Osaka, Japan. This technology includes an addition of 1.5% Calcium to the Aluminum melt for adjusting the viscosity. Calcium is introduced to the molten Aluminum at 680°C and stirred for 6 minutes in an ambient atmosphere. The thickened Aluminum melt is poured into a casting mould and stirred with an addition of powdered TiH_2 (foaming agent) by using a rotating impeller. If a sufficient amount of the hydride is added (usually 1.6%) the foaming agent decomposes under the influence of heat and releases hydrogen gas. Thereby, the foam expands and fills up the mould within 15 minutes. It is cooled down by fans in the mould and solidifies as a block with porosity between 89% and 93%. A cast Alporas block can be as large as 2.05 m (length) $\times$ 0.65 m (width) $\times$ 0.45 m (height) and weighs 160 kg. The blocks can be cut into sheets of the required thickness.

2.1.1.3 Other processes

The GASAR process is based on the varying solubility of hydrogen depending on the pressure. The metal is melted in an autoclave and then brought under high pressure that

allows solving of a high amount of hydrogen. This saturated melt is poured into a mould within the autoclave. This is followed by a directional solidification of the melt under reduced pressure, which causes a precipitation of the hydrogen gas at the solidification front. The porosity achievable is usually lower, from 5% to 75% [12].

Other technologies are based on the well-known casting process. To build a mould, these technologies are working with a reticulated PU-foam that is filled with slurry of heat resistant material. After drying the polymer is removed and the molten metal is cast into the resulting mould. Then the mould material is removed by pressurized water. The metallic foam obtained will have exactly the foam structure of the original PU-foam. Porosities typically range from 80% to 97%. This process differs from those described above in that it produces foam with open cells [13].

2.1.2 Fabrication based on metal powder mixing process

2.1.2.1 Expansion with a gas released by a foaming agent

Figure 2.3 Production of Aluminum foams with the IFAM-Technology [12]

This technology starts with the mixing of the metal powders (pure metal, alloy or powder blend) with a foaming agent (for Aluminum and its alloys usually 0.4 – 0.6 % TiH₂). The mixture is compacted to a dense, semi-finished product. In the IFAM-process

(Fraunhofer-Institute in Bremen, Germany) the material is compacted by uni-axial compression, CIP, powder rolling or extrusion depending on the required shape. The MEPURA process [20] uses a continuous extrusion technology for the compaction of the mixture.

After compression, the mixer is heat-treated up to the melting point of the matrix metal and above the decomposition temperature of the blowing agent. At this temperature the foaming agent decomposes and releases hydrogen gas. This gas leads to an expansion of the material resulting in a highly porous structure with closed cells. By cooling under the melting point the foaming process is stopped. The porosities range from 60% to 85%.

2.1.2.2 Process with an entrapped gas

In this technology, a hermetic lockable container is filled with the Aluminum powder. After that, a gas e.g. Argon is pressed into the powder. The gas fills all spaces between the powder particles. If this mixture is heated, the powder particles melt together and entrap the gas. The metal block is then rolled and heated, and the entrapped gas expands and finally metal foam is resulted [13].

2.1.2.3 Process by the spacer method

In this method, commercially available 99.9% Aluminum powder with an average size of about 3 μ m and NaCl particles with particles sizes of 300–425 μ m are prepared. The Aluminum powder and NaCl particles are thoroughly mixed in a volume ratio of 1:9 in an agate mortar. The mixture is compacted at a pressure of 20 MPa and sintered at 843 K for 600 s by spark plasma sintering using the apparatus SPS-515S manufactured by Sumitomo Coal Mining in Tokyo, Japan. The sintered compacts are put into running water to remove NaCl particles [13].

2.2 Properties of Porous Aluminum

Aluminum foams are isotropic porous materials with several unusual properties that make them especially suitable for some applications. Due to their low densities, some of

the foams with closed porosity can float in water. The electrical and thermal conductivities of Aluminum foam are lower than dense Aluminum. The strength is lower than conventional dense Aluminum and reduces with decreasing density. Foams are stable at temperatures up to the melting point. They are incombustible and non-toxic. Table 2.1 provides a comparison of mechanical properties of the Alporas Aluminum foam with porosity of 91.48 % produced by GLEICH [18] with those of solid Aluminum [25].

Table 2.1 Mechanical properties of Alporal and solid Aluminum

Parameter	99.6% Al	Porous Al
Density (g/cm ³)	2.7	0.23
Young's Modulus (Gpa)	70	1.1
Shear Modulus (Gpa)	26	0.33
Shear Strength (Mpa)	30	1.2
Tensile Strength (Mpa)	110	1.6
Peak Stress (Compression) (Mpa)	35	1.9
Yield Strength Rp0,2 (Mpa)	100	1.5
Poisson's Ratio	0.35	0.33

For ease of understanding of Table 2.1, the definitions of the various parameters are explained briefly as follows:

- Young's Modulus is a measure of the stiffness of a material.
- Shear Modulus is defined as the ratio of shear stress to the shear strain. It is concerned with the deformation of a solid when it experiences a force parallel to one of its surfaces while its opposite face experiences an opposing force.
- Shear Strength is a term used to describe the strength of a material or component against the type of yield or structural failure where the material or component fails in shear.
- Tensile Strength measures the engineering stress applied (to something such as rope, wire, or a structural beam) at the point when it fails.

- Peak Stress is used to describe the maximum strength at which point significant plastic deformation or yielding occurs due to an applied shear stress.
- Yield Strength is defined in as the stress at which a material begins to deform plastically.
- Poisson's Ratio is the ratio of the relative contraction strain divided by the relative extension strain or axial strain (in direction of the applied load).

From the comparison in Table 2.1, it is expected that the mechanical strength of porous Aluminum will not be as good as solid Aluminum. However, its high porosity (91.48 %) make this material is very light (about 10% of that of pure Aluminum) and it is much softer than pure Aluminum. The softness indicates that the material is much easier to process with when it is used for construction application. The foam blocks can be drilled and cut with normal mechanical tools. It is also easy to drive nails into the foam and to use chemical adhesives to stick pieces of Aluminum foam to each other or to other materials. Table 2.2 is another comparison of mechanical properties of porous Aluminum with wood [26, 27] and concrete [25], which are widely used as building construction materials.

Table 2.2 Mechanical Properties of Porous Al, Wood and Concrete

Parameter	Porous Al	Typical Wood	Concrete
Density (g/cm ³)	0.23	0.4 to 0.8	1.7 to 2.4
Young's Modulus (Gpa)	1.1	7 to 11	18 to 30
Shear Modulus (Gpa)	0.33	0.5 to 1.1	Not Available
Shear Strength (Mpa)	1.2	4 to 8	Not Available
Tensile Strength (Mpa)	1.6	1.5 to 3	40
Peak Stress (Mpa)	1.9	2 to 5	40
Yield Strength Rp0,2 (Mpa)	1.5	Not Available	Not Available
Poisson's Ratio	0.33	0.2 to 0.5	Not Available

Table 2.2 shows that the density of porous Aluminum is even lower than typical wood. In general, the mechanical properties of porous Aluminum are comparable to those of

typical wood. However, the mechanical strength of the porous Aluminum can be improved by applying casting surface and making the pore size more homogenous. One obvious advantage is that porous Aluminum has much higher electrical conductivity, which makes it a better EM shielding material as compared to concrete and wood.

Chapter 3 Shielding Effectiveness Test Methods

In order to assess the shielding effectiveness (SE) of porous Aluminum samples, suitable shielding test methods are reviewed. Two commonly adopted standards, IEEE STD 299 (standard test method for measuring the shielding effectiveness of electromagnetic shielding enclosure) [28] and ASTM D4935-99 (standard test method for measuring the electromagnetic shielding effectiveness of planar materials) [29], will be discussed.

The detailed test procedures have been reported in the two standards. This chapter will only describe the two test standards briefly. Sections 3.1 and 3.2 will describe the IEEE STD 299 the ASTM D4935-99, respectively. The fabrications of the necessary test jigs for the SE measurement are discussed in Section 3.3. Finally, Section 3.4 addresses the challenges faced when applying these two methods to access the SE of porous Aluminum sample.

3.1 IEEE STD 299 Test Method

This method provides the basic measurement procedures and techniques determining the SE of a room-type shielded enclosure at frequencies from 14 kHz to 18 GHz. Enclosure-under-test can be either single-shield or double-shield structures of various constructions, such as bolted demountable, welded, or integral with building and made of materials such as steel plate, copper or Aluminum sheet, screening hardware cloth or metal foil all can be tested with this method.

An electromagnetic field transmitter is placed outside the shielded enclosure and an electromagnetic field detector is placed inside the enclosure. The setup of the method changes slightly according to frequency range. However, each procedure requires measurements to be made over all walls containing doors and around room penetrations, such as air vents, power-line filter panels, coaxial-connector panels, compressed air lines, water pipes, telephone filter panels, etc, as shown in Figure 3.1. These measurement procedures shall be used for standard locations and standard frequencies for which the

procedures are valid. These frequencies are: 14 kHz to 20 MHz (low frequency range), 300 MHz to 1 GHz (mid frequency range) and 1.7 to 18 GHz (high frequency range).

Figure 3.1 Test Positions [28]

3.1.1 Test Procedures

The SE test is divided into three frequency ranges, namely: low frequencies (14 kHz to

20 MHz), mid frequencies (300 MHz to 1 GHz) and high frequencies (1.7 to 18 GHz). Of these three frequency ranges, seven frequency bands are chosen and at least one frequency out of each band has to be measured. Suitable antennas are chosen for frequencies in different frequency ranges, as listed in Table 3.1.

Table 3.1 Standard Measurement Frequencies and Antenna Type

Standard Frequency	Field Type to Measure	Antenna Type
Low Frequency Range 14-16 kHz 140-160 kHz 14-16 MHz	H Field	Small Loop
Mid Frequency range 300-400 MHz 850-1000 MHz	Plane Wave	Dipole
High Frequency Range 8.5-10.5 GHz 16-18 GHz	Plane Wave	Horn

3.1.1.1 Low Frequency Range Measurement

The equipment set up of this measurement is described in Figure 3.2. The transmitting antenna is a 0.3 m diameter loop. At the lower frequency, a signal source with an amplifier is usually adequate to supply the loop current if a suitable coupling transformer is used. At higher frequencies, a higher power signal source and resonant matching may be needed. The detector should be a loop identical to the transmitting loop connected to a field strength meter or a spectrum analyzer.

Figure 3.2 Low Frequency Range Test Setup [28]

Before the measurement, a reference field measurement is made. This is done by placing two loop antennas at a separation distance of 0.6 m and without the shield barrier in between. After the reference field measurement, another measurement with the shield barrier in place is performed. The transmitting and receiving loops are each placed 0.3 m from the shielding barrier. The received signal is then recorded. The SE in decibel is calculated by subtracting the received signal in dBm from the reference signal in dBm obtained earlier.

3.1.1.2 Mid Frequency Range Measurements

The measurement set up for the mid frequency range test is shown in Figure 3.3. At this frequency range, the SE introduced by the shielding enclosure is usually quite high. Thus, a signal generator capable of delivering at least 10 W into a matched load is required. The generator is normally matched to an unbalanced-to-balanced (balun) transformer. The balanced output is matched to a balanced dipole antenna that is half-wavelength resonant at the test frequency.

Figure 3.3 Mid-Frequency Range Test Setup [28]

The detecting antenna is an electric dipole whose overall electrical length is not greater than one-eighth of a wavelength (to limit effects due to a change in impedance from the reference value caused by proximity to a shield barrier). The output of the antenna will be connected through a balun to a coaxial cable and then to an attenuator that connects to the field-strength meter. The measurement procedure is similar to that of low frequency range measurement except that the transmitting antenna is placed at 1.3 meters away from the shielding barrier. It should also be noticed that at this frequency range, care should be taken to protect personnel from RF hazards.

3.1.1.3 High Frequency Range Measurement

The measurement setup for high frequency range SE test is given in Figure 3.4.

Figure 3.4 High Frequency Range Measurement Setup [28]

The measurement procedure is similar to those of the previous two frequency ranges.

3.2 ASTM D4935-99 Test Method

The ASTM test method provides a procedure for measuring the shielding effectiveness (SE) of a planar material due to a transverse electromagnetic (TEM) wave. Depending on the dimensions of the specimen holder, the frequency range for SE measurement varies. For the given dimensions of the specimen holder specified in the ASTM standard, the test frequency range is limited between 30 MHz and 1.5 GHz. Higher frequency range requires a new test jig of smaller dimensions to prevent higher order non-TEM wave propagation in the test jig.

If the material under test is electrically thin, isotropic and has frequency-independent electrical properties (conductivity, permittivity and permeability), only a few measurement frequencies are needed because the SE values will be independent of frequency. If the material is not electrically thin or if any of the parameters is frequency dependent, measurements should be made at many frequencies within the band of interest [29].

3.2.1 Test Setup

The test setup is illustrated in Figure 3.5

Figure 3.5 General Test Setup [29]

The most crucial part of this test method is the specimen holder. The design of the specimen holder will be described later. A spectrum analyzer or a field strength meter is typically chosen as the receiving device. In order to transmit TEM electromagnetic wave between specific components without causing interference with other components, double-shielded coaxial cable and N-type connector are recommended as they provide lower leakage and are more reliable. A 10 dB, 50-Ω attenuator is connected to each end of the specimen holder. These attenuators are used to provide impedance matching in the whole system as the power reflected by the material may change the generator impedance loading. To measure the SE of a material-under-test, two samples of the same type of material have to be prepared. One sample is the called the “reference” and another is called the “load”, as shown in Figure 3.6.

Figure 3.6 Illustrations of Reference and Load Specimens [29]

3.2.2 Measurement Procedure

The measurement procedure is as follows:

- i. List down all the frequencies of interests for the SE measurement. As the specimen mounting requires some time and effort, it is more efficient to record values at all frequencies for the reference specimen. Once the readings for reference specimen are taken, change to the load specimen and then record the values again at the same frequencies.
- ii. To insert the specimen, use a support structure (a large roll of tape or special stand) to support the specimen holder in a vertical position. Remove the two nylon screws, turn the holder end for end, remove the other two nylon screws, and carefully lift off the upper half of the holder. An indented, soft foam pad is useful for holding this upper half of the specimen holder while continuing the installation or removal of specimens. Place the two pieces of the reference specimen on the flange of the bottom half of the specimen holder and ensure that the disk for the center conductor is aligned. Use small amounts of transparent tape as needed. Replace the half of the specimen holder that has been removed so that the holes for the nylon screws are aligned. Reinstall two nylon screws. Turn the holder end for end and then reinstall the other two nylon screws. Reconnect the coaxial cables.
- iii. Measure the received power (or voltage) while using the reference specimen. Record the measured received values as P_2 or V_2 at each frequency.
- iv. Replace the reference specimen with the load specimen. Measure the received power with the load specimen. Record these measured values as P_1 or V_1 at the same frequencies.
- v. If the measured results are in decibel, the SE value can be easily computed as

$P_2 - P_1$ or $V_2 - V_1$. If the measured results are in units of W or V, they need to be converted to decibel and then the SE is calculated accordingly.

3.3 Design of the Test Jigs for the Test Methods

3.3.1 Design of Test Jig for the IEEE Method

The IEEE test method described in Section 3.1 is for measuring the SE of large shielded enclosure. This project needs to measure the shielding effectiveness of a single piece of planer porous Aluminum. In view of that, an existing shielded room in NTU is used with the aim to measure the SE of the porous Aluminum panel. Hence, in this project the existing feed through panel on one of the walls of the shielded room is removed. A test jig for holding the material is mounted onto the wall of the shielded room, as illustrated in Figure 3.7.

Figure 3.7 Test Jig for the IEEE Test Method

A test jig is designed by using a piece of solid Aluminum frame, which has identical screw tracks with the original feed through panel. The frame has a square hole of 21 cm x 21 cm. To determine the SE of the porous Aluminum panel, a reference reading is

taken with the hole opened and another reading with the hole covered by the porous Aluminum sample. An edge cover plate made of stainless steel is made to line all the edges of the test sample and is tighten by eight screws on each side to ensure good electrical contact is achieved between the porous Aluminum sample and the shielded room. Shielding gasket is also added to improve the electrical contact.

3.3.2 Design of Specimen Holder for ASTM Method

The detailed mechanical design for the specimen holder for the ASTM method is shown in Figures 3.8 to 3.12. The specimen holder is an enlarged, coaxial transmission line with special taper sections and notched matching grooves to maintain a characteristic impedance of 50 Ω throughout the entire length of the holder. This characteristic impedance is checked with a time domain TDR, and any variations greater than 0.5 Ω needs to be corrected.

Figure 3.8 Taper Sections for Center Conductor [29]

There are three important aspects to this design. First, a pair of flanges in the middle of the structure holds the specimen. This allows capacitive coupling of energy into

insulating materials through displacement current. Second, a reference specimen of the same thickness and electrical properties as the load specimen causes the same discontinuity in the transmission line as is caused by the load specimen. Third, non-conductive (nylon) screws are used to connect the two sections of the holder together during tests. This prevents conduction currents from dominating the desired displacement currents necessary for the correct operation of this specimen holder [29].

Figure 3.9 Taper Sections for Outer Conductor [29]

Figure 3.10 Pressure Ring for Outer Conductor [29]

Figure 3.11 Flange Section for Outer Conductor [29]

Figure 3.12 Drawing of a Half Section [29]

Figure 3.13 shows the various parts of the actual specimen holder fabricated by the author and Figure 3.14 shows the fully assembled specimen holder

Figure 3.13 Various Parts of Half Section of Specimen Holder

Figure 3.14 Fully Assembled Specimen Holder

3.4 Advantages and Disadvantages

The IEEE test method has the following advantages and disadvantages:

Advantages:

- Utilize an existing shielded room and the only modification is to make a test jig for holding the sample-under-test, making it cost effective.
- Relatively easy to attach the sample onto test jig and has the flexibility to cater for very different sample thickness.

Disadvantages:

- Require a larger sample size as compared to ASTM method.
- Require different antennas for different frequency ranges. Changing and positioning antennas can be time-consuming.
- The method uses transmitting device and require due diligence to avoid RF hazards to human health at certain frequencies.

The advantages and disadvantages of the ASTM standard method are summarized as follows:

Advantages:

- The EM wave is TEM in nature and no problem with the near-field issue as compared to the IEEE test method, making it suitable for SE measurement of planer material.
- Dimension of sample under test is smaller.
- As whole frequency range can be tested once the material is attached, the measurement is efficient.
- As the design is based on transmission line theory, the EM wave only propagates within the specimen holder. Hence, there is no concern for RF hazards.

Disadvantages:

- To acquire accurate result, the thickness of the sample must be electrically thin ($<1\%$ of the wavelength at the maximum frequency of interest). This can be difficult to achieve for certain materials. Especially in this project, the pore size in porous Aluminum can easily exceed the required thickness.
- As there are many parts in the test jig and there is a very high requirement on the precision of each part to make sure that the test jig is properly assembled.
- The fabrication cost for making all the parts with high precision can be expensive.

Chapter 4 Electrical Conductivity Measurement

As mentioned in the earlier chapter, EM shielding effectiveness of a material depends very much on its electrical properties such as conductivity and permeability. As porous Aluminum has the same permeability as air, the only electrical property needs to be determined is its conductivity. Once the electrical conductivity of the porous Aluminum is known, the intrinsic SE can be easily estimated. A commonly adopted method to measure conductivity of a planar material is the four-point method [30, 31]. This method requires the surface of the material to be smooth and well polished. Unfortunately, the surface of porous Aluminum can never be smooth and flat due to the pores of the material. Hence, the four-point test method cannot be used to measure the conductivity of porous metal.

This chapter proposes a simple and easy to implement method to measure the electrical conductivity of the porous Aluminum sample.

4.1 Measurement Method

Under DC condition, the resistivity of a rectangular piece of material can be determined by:

$$\rho = \frac{A}{L} \times R \quad (\Omega \cdot \text{m}) \quad (4.1)$$

Where A is the area in m^2 of the surface perpendicular the direction of current flow, L in m is the length of the material sample and R in Ω is the resistance of the material sample.

If the resistance of porous Aluminum sample is known, the electrical resistivity can be calculated and eventually the electrical conductivity can be determined through the reciprocal of resistivity. The most common laboratory instrument for measuring the resistance is the multi-meter. However, the smallest range of resistance that could be measured using a normal multi-meter is around a few hundred $\text{m}\Omega$. It is impossible to measure the resistance of porous Aluminum, which could be as low as a few $\text{m}\Omega$.

Another alternative to measure such a low resistance is to pass a high current through the material and the measure the voltage across it. However, the current pass through the material must be in the range of several tens or hundreds of Amp in order to measure any noticeable voltage across the sample. Without the use of expensive high-current power supply, a practical and low cost solution is proposed. A very high-gain amplifier is designed to amplify the voltage across porous Aluminum sample so that the current passing through the material can be made small and can be easily supplied by normal power supply.

4.2 Proposed Circuit for Low Resistance Measurement

4.2.1 High Gain Amplifier Design

As explained earlier, the purpose of designing an amplifier with very high gain is to measure the voltage across porous Aluminum sample when a reasonable amount of current passing through it, which could be in the range of a few mV. The amplifier amplifies this low voltage so that the voltage across the sample after amplification can be measurable by a normal multi-meter. To fulfill this objective, the intended voltage gain is expected to be around 1,000, so that the amplified voltage will be more than 1 V, which can be measured easily using a multi-meter with reasonable accuracy. Figure 4.1 shows the proposed design of the high gain amplifier [33].

Figure 4.1 Design of High Gain Amplifier

The differential amplifier configuration has been selected. The LM1458N op amp is

chosen as it is readily available with low cost [34].

For the amplifier configuration shown in Figure 4.1, the output voltage can be expressed as follows [35]:

$$V_{out} = (V_1 - V_2) \times \frac{R_f}{R_i} \quad (4.2)$$

With the selected resistor values in Figure 4.1, the designed voltage gain of this differential amplifier is 1000. The power supplies are chosen as ± 18 V, as these are the maximum supply voltages for LM1458N, so that a wide dynamic range for the amplifier is achieved.

4.2.1 DC Offset Compensation

Ideally, the output voltage of the amplifier V_{out} should be zero if no voltage is applied at the two differential input terminals of the amplifier. In reality, the output will never be zero due to DC offset. The cause of the DC offset voltage is the inherent mismatch of the transistors and components within the op amp. These effects produce imbalance bias currents that flow through the input circuit, and primarily the input devices, resulting in a non-zero differential voltage at the input terminals of the op amp. Figure 4.2 shows the basic blocks of an op amp.

Figure 4.2 Simplified Circuit Blocks of Op Amp [36]

Q_1 is the non-inverting input terminal transistor and Q_2 is the inverting input transistor. The current source provides biasing for the two transistors. In ideal case, each leg of the circuit is perfectly balanced so that one half of the current flows through each transistor ($I_{Q1} = I_{Q2} = I_{REF}/2$) and the inverting and non-inverting inputs are at the same potential. In practical cases, mismatches in R , Q_1 , and Q_2 cause the bias currents to both transistors to be unequal. The base (or gate) voltages of the transistors then become unequal, creating a finite differential voltage, V_{io} [33, 36].

For the amplifier designed in Figure 4.2, the output voltage V_{out} measured when the two input terminals are both opened is found to be 0.86 V. If the voltage gain is 1000, it indicates that the DC input offset voltage is about 0.86 mV with the non-inverting input terminal at higher potential. In order to null this offset voltage, a DC offset compensation circuit is needed to provide a finite voltage to the inverting input terminal of the amplifier. The purpose of the circuit is to provide a voltage that is same as the V_{io} . Figure 4.3 shows the amplifier with the DC offset compensation circuit.

The circuit within the dotted box is the DC offset compensation circuit. It is basically a voltage divider circuit consists of a 500 k Ω variable resistor in series with a 100 Ω fixed resistor and powered by a 1V supply. The voltage across R will be used to cancel the effect of input DC offset voltage. The voltage across R can vary from 0 V to 1 V by adjusting the variable resistor. By carefully adjusting the variable resistor, one can produce a voltage that is equal to V_{io} and as a result, V_{out} becomes zero when there is no voltage applied to two input terminals of the amplifier. At this situation, the voltages at the two input terminals with respect to ground are now the same. With the inverting input terminal unchanged, any voltage applied at the non-inverting input terminal will be the resultant differential voltage between the two input terminals.

Figure 4.3 Amplifier with DC Compensation Circuit

4.3 Voltage Gain of Amplifier

Once the input offset voltage has been compensated, the next step is to validate the voltage gain through measurement. For validation, a 3 kΩ resistor with the actual measured value of 3.047 kΩ is connected in series with a very small resistor. As it is difficult to obtain resistor values in the range of mΩ in the market, several 1 Ω identical precision resistors are connected in parallel, so that we could achieve a resultant small resistance. The measured resistance of the 1 Ω resistor is found to be 1.07 Ω. Therefore the resultant resistance of the identical resistors in parallel is $R_s = 1.07/n$ Ω, where n is the number of identical resistors in parallel. The 3.047 kΩ resistor and the parallel combination of the 1.07 Ω resistors formed a voltage divider and powered by a 5 V DC voltage source, as shown in Figure 4.4. The 3.047 kΩ resistor and the 5 V voltage source function as a constant current source to provide a well-defined current to the small resistor R_s . The voltage across R_s is very small and is amplified by the high-gain amplifier. As the resistance of the circuit is known, current passing through the circuit and voltage across R_s can be calculated. As the input resistance of the amplifier is much larger, the loading effect due to the amplifier’s input is negligible and therefore voltage across R_s is not affected by this input resistance. The output voltage V_{out} of the amplifier can now be easily measured with a multi-meter.

Figure 4.4 Voltage Divider Circuit

The voltage gain of the amplifier can be determined by:

$$A_V = \frac{V_{out}}{V_{in}} \quad (4.3)$$

Figure 4.5 shows the final overall schematic for the measurement of the amplifier voltage gain.

Figure 4.5 Connection of Amplifier Circuit for Voltage Gain Measurement

To measure the voltage gain of the amplifier, the variable resistor in the DC offset compensation circuit is first adjusted until the V_{out} is 0. After that, the voltage divider circuit is connected to the non-inverting input of the amplifier and the voltages across R_s for $n = 1, 2, 3, 4, 6, 8, 10, 12, 14$ and 16 , are measured. To ensure that the contact resistance to R_s is minimized, the wire connection is made very short (cooper wire less than 2 cm) and is soldered directly to s R_s .

For each value of R_s , the measurement is performed several times to ensure repeatable readings. The measured results and voltage gain are tabulated in Table 4.1.

Table 4.1 Measured Amplifier Voltage Gain

N	$R_s (\Omega)$	$V_{rs} (mV)$	$V_{out} (V)$	Gain	Error (%)
1	1.07	1.755	1.715	977	-2.3
2	0.535	0.8778	0.865	985	-1.5
3	0.356	0.5858	0.581	992	-0.8
4	0.2675	0.4389	0.435	991	-0.9
6	0.1783	0.2926	0.294	1005	+0.5
8	0.1338	0.2195	0.214	975	-2.5
10	0.107	0.1756	0.180	1025	+2.5
12	0.0892	0.1464	0.149	1018	+1.8
14	0.0764	0.1254	0.1295	1033	+3.3
16	0.0669	0.1097	0.112	1021	+2.1

Table 4.1 shows that the measured voltage gain is in good agreement with the designed voltage gain of 1000, even when R_s becomes very small. The agreement is within -2.5% to +3.3%. Hence, it is appropriate to use 1000 as the voltage gain of the amplifier in subsequent measurement of electrical conductivity.

4.4 Validation Using Conductive Wire

Since the amplifier voltage gain has been validated, the circuit is now ready for electrical conductivity measurement. To ensure that the proposed measurement method works well, a conductive wire with known electrical conductivity is used as a sample under test. The measured conductivity using this method will then compare with the known electrical conductivity of the conductive wire for verification purpose.

Similar voltage divider circuit described in Figure 4.3 will be used but the resistor R_s is now replaced by the material under test, for this case, a conductive wire. The conductive wire used for the verification is the commonly found copper alloy wire. Its diameter is 0.6 mm with a length of 1 m. The electrical conductivity for pure copper is 5.8×10^7 S/m.

For copper alloy, the electrical conductivity is expected to be slightly lower due to the addition of other composition such as steel, which has a lower conductivity. It is reported that copper alloy wire has an electrical conductivity of around 70% to 80% of pure copper. Hence, the expected electrical conductivity of copper alloy should be somewhere between 4×10^7 S/m and 4.6×10^7 S/m [37, 38]. The measurement setup with the material-under-test is shown in Figure 4.6.

Figure 4.6 Connection for Material under Test

The copper alloy wire (material-under-test) is connected in series with the 3.047 kΩ resistor and powered by a 5 V DC voltage. As the estimated resistance of the 1 m copper alloy wire is less than 0.1 Ω, the loading effect due to the amplifier input has negligible effect on measurement. The current pass through the material-under-test can be calculated by:

$$I = \frac{V}{R} \approx \frac{5}{3047} = 1.64 \text{ mA}$$

The measured voltage from the output of the amplifier is 0.131V. So the voltage across the copper wire is 0.131V/1000, which is 0.131 mV. With known voltage across the wire and the current through the wire, the resistance of the copper alloy wire is calculated to be 79.88 mΩ. The resistivity of copper wire can then be determined by:

$$\rho = \frac{0.07988}{1} \times (0.0003)^2 \times \pi = 22.58 \times 10^{-9} \text{ } \Omega\text{-m}$$

Taking the reciprocal of the resistivity, the electrical conductivity is found to be

$4.43 \times 10^7 \text{ S/m}$.

The same measurement is repeated with 1.5 m of 0.66 mm Copper alloywire and 0.5 m of 0.4 mm Copper alloy wire. The measured output voltages of the amplifier for these two wires are 0.193 V and 0.15 V, respectively. Using the same calculation procedure, the conductivity for these two wires are found to be $4.51 \times 10^7 \text{ S/m}$ and $4.29 \times 10^7 \text{ S/m}$, restively. From these measured results, the conductivity obtained is consistence, as the actual electrical conductivity of the copper alloy is somewhere between $4 \times 10^7 \text{ S/m}$ and $4.6 \times 10^7 \text{ S/m}$.

4.5 Conductivity Measurement of Porous Aluminum

4.5.1 Measurement Procedure and Setup

With the measurement method validated, now it is ready to measure the electrical conductivity of porous Aluminum, the material-under-test in the voltage divider circuit described in Figure 4.6 is now replaced with a porous Aluminum sample. A porous Aluminum sample of rectangular shape with dimension of 2 cm × 2 cm × 30 cm is prepared. To minimize the measurement error due to contact resistance, copper foils are clamped at both ends of the porous Aluminum block test with a G-type plastic clamp and the copper foils are soldered to very short copper wire to facilitate the measurement. Figure 4.7 shows the measurement setup for electrical conductivity measurement of porous Aluminum.

Figure 4.7 Measurement Setup for Conductivity Measurement

4.5.2 Measurement Result

As the $30.9\ \Omega$ is expected to be much larger than the resistance of the material-under-test, the 2 V supply voltage and the $30.9\ \Omega$ resistor again functions as a constant current source. The current passing through material-under-test is found to be 64.7 mA. The output of the amplifier records a voltage of 0.824 V and therefore the voltage across the porous Aluminum sample is 0.824 mV. With the known current and voltage, the resistance of the porous Aluminum sample is found to be $12.74\ \text{m}\Omega$. With the known length and cross-sectional area of the porous Aluminum sample, the resistivity of the sample can be calculated by:

$$\rho = \frac{0.02^2}{0.3} \times 0.01274 = 1.699 \times 10^{-5}\ \Omega\text{-m}.$$

Taking its reciprocal, the conductivity of porous Aluminum is found to be $5.887 \times 10^4\ \text{S/m}$.

4.5.3 Verification of Measurement Result

For measuring very low resistance, the contact resistance must be considered or it may cause large error to the measured result. In the previous measurement, the contact resistance for the wire connecting the porous aluminum to the ground is not eliminated. So it is necessary to check the accuracy of the measurement result. To verify, the four point method is use. The verification circuit is given in figure 4.8. In this circuit, another amplifier with same setting and same amplification is used. The circuit in the dotted box is now serving as a constant current source. The non-inverting input terminals of the two amplifiers are then directly connected to the two ends of porous aluminum. By doing so, the out put of the two amplifiers V_{out1} and V_{out2} are the exact voltage at both ends of the porous aluminum without the effect of contact resistances from both ends. By subtracting V_{out1} and V_{out2} , the voltage across the porous aluminum after 1,000 times amplification can be calculated. And subsequently, the resistivity and conductivity of the porous aluminum can be calculated.

Figure 4.8 Four Point Method Verification Circuit

In this measurement, the output at V_{out1} is recorded at 0.823 V and the output at V_{out2} is recorded at 0.008 V. So the Voltage across the porous aluminum is 0.815 mv. As we already know the current across the material is 64.7 mA. Hence the resistance of the porous aluminum is calculated to be 12.597 mΩ. With the known length and cross-sectional area of the porous Aluminum sample, the resistivity of the sample can be calculated by:

$$\rho = \frac{0.02^2}{0.3} \times 0.012597 = 1.6796 \times 10^{-5} \text{ } \Omega\text{-m.}$$

So the conductivity of the porous aluminum is ρ^{-1} equals to 5.954×10^4 S/m. Comparing with the previous measured conductivity, it is found that the error during the previous measurement is only 1.13 % which already shows good accuracy for the conductivity of the porous aluminum.

4.6 Shielding Effectiveness of Porous Aluminum

The measured electrical conductivity in Section 4.5 is the conductivity of porous aluminum under DC condition. The conductivity of a metallic material is almost constant up to a certain frequency while relaxation happens [39]. This thesis only interested in SE up to 1 GHz, which is well below the frequency where relaxation happens. Hence, it is still appropriate to compute the shielding effectiveness with the measured DC conductivity. With the measured electrical conductivity from Section 4.5, the resultant shielding effectiveness (SE) of a 1 mm thick porous Aluminum, under far-field condition, can be estimated with Equations (1.8) and (1.9). Table 4.2 shows the absorption loss, reflection loss and resultant SE for different frequencies.

Table 4.2 Calculated SE for 1 mm Thick Alporas Porous Aluminum

Frequency (MHz)	Absorption Loss (dB)	Reflection Loss (dB)	SE (dB)
0.3	2.3	83.4	85.7
1	4.2	78.2	82.4
10	13.4	68.2	81.6
100	42	58.2	100.2
200	59.2	55.2	114.4
350	78.3	52.7	131.0
500	93.9	51.2	145.1
750	115	49.4	164.4
1000	133.6	48.2	181.8

Table 4.2 shows that in the frequency range of 300 kHz to 1 GHz, intrinsic SE of at least 80 dB is achievable for porous Aluminum, even with 90% porosity. Hence, it is feasible to use porous Aluminum for most shielding applications.

Chapter 5 Shielding Effectiveness Test and Simulation

The two common test methods for SE measurement have been reviewed in Chapter 3. The necessary test jigs associated with the test methods have also been fabricated. The porous Aluminum “Alporas” manufactured by GELICH [18] will be tested using IEEE test method as it is commercially available in large enough size to construct a shielded enclosure. Also, the thickness of Alporas cannot be less than 5 mm due to limitation of the fabrication process. The ASTM test method requires the thickness of the sample not to be more than 1.5 mm. Hence, the ASTM test method will not be suitable for the SE measurement of Alporas samples.

In this chapter, SE measurement results for the Alporas samples using IEEE test method are first presented. It is followed by simulation of SE of Alporas using a 3D full-wave electromagnetic simulation tool [40]. Finally, a shielded enclosure using Alporas panels is assembled and the SE of this enclosure is measured to show a more realistic SE performance for practical applications.

5.1 Shielding Effectiveness Measurement for Alporas using IEEE Test Method

The test is performed using the test jig described in section 3.3.1. Due to the limitation of test space, the distances for locating the transmitting and receiving antennas are modified slightly for midrange measurement (refer to Section 3.1.2). Both the transmitting and receiving antennas are placed at a distance of 0.5 m from the shield barrier.

Table 5.1 lists the instruments used in this measurement. The signal generator is connected to the transmitting antenna as the electromagnetic field source. A spectrum analyzer is connected to the receiving antenna to measure the received signal level. To improve the dynamic range of the SE measurement, a 30 dB gain pre-amplifier is connected between the spectrum analyzer and the receiving antenna. At low frequency range, two identical passive loop antennas are used as transmitting and receiving

antennas. At midrange frequency, a pair of bi-log antenna that covers a frequency range of 30 MHz to 1 GHz is employed as transmitting and receiving antennas.

Table 5.1 List of SE Test Instruments

Instrument	Model	S/N	Quantity
IFR Signal Generator	2023A	202301-208	1
HP Spectrum Analyzer	8591A	2944U00467	1
AR 30 dB Pre Amplifier	LN100A	0320194	1
ETS Loop Antenna	6509	00062948 & 88121133	2
Schwarzbeck Tri-Log	VULB 9160	3066 & 3067	2

The IEEE procedure described in Section 3.1.2 is followed except that a dynamic range check is done before introducing the shield barrier. Instead of measuring 7 frequencies from the 7 frequency bands given in Section 3.1.2, a total number of 24 frequencies are measured so that the SE across the full frequency range can be observed clearly. These frequencies are: 250 kHz, 500 kHz, 1 MHz, 5 MHz, 10 MHz, 20 MHz, 30 MHz, 40 MHz, 50 MHz, 60 MHz, 70 MHz, 80 MHz, 90 MHz, 100 MHz, 200 MHz, 300 MHz, 400 MHz, 500 MHz, 600 MHz, 700 MHz, 800 MHz, 900 MHz and 1000 MHz.

For each of the test frequencies, a reference signal is measured. To measure the reference signal, the hole on the test jig is left open. The transmitting antenna is placed outside the shielded room and receiving antenna is placed inside the shielded room. The separation distance for between the antennas is 0.6 m for low range test and 1 m for mid-range test.

The dynamic range check is done by leaving the center part of test jig open and the signal transmitted through is measured and the noise floor level is also recorded. By doing so, the dynamic range of shielding effectiveness of the existing measurement setup can be determined.

Alporas samples of identical size of 21 cm × 21 cm but different thicknesses (0.6 cm, 1 cm and 2 cm) are tested. Figure 5.1 shows a piece of Alporas sample mounted onto the

shielded room with the test jig.

Figure 5.1 Alporas Sample Fixed to Shielded Room

To ensure good electrical contact between the sample and the test jig, shielding gasket is applied along the edges of the test jig to make sure that good electrical contact is maintained when the screws are tightened. Conductive tapes are also applied to prevent as much field leakage as possible from the edges of the test jig.

Once the sample is properly fixed onto the wall of the shielded room, the antennas are placed at the respective positions and connected to the equipments for the SE measurement. Figure 5.2 shows the position of the receiving antenna in the shielded room. At measurement frequency higher than 500 MHz, it is necessary to stay far away from the transmitting antenna and keep the power-on time as short as possible to minimize possible RF human hazards. Usually, the power-on time is less than 10 minutes for the measurement.

A signal generator with output set at level of 10 dBm is injected to the transmitting antenna and the received signal level is monitored using a spectrum analyzer, which is placed inside the shielded room.

Figure 5.2 Position of Antenna

The SE of porous Aluminum samples are shown in figure 5.3.

Figure 5.3 Shielding Effectiveness of the Samples with Different Thickness

In Figure 5.3, the blue, pink and yellow curves represent the SE for samples of thicknesses 0.6 cm, 1 cm and 2 cm, respectively. Comparison of the three curves shows that the SE for the three different thicknesses exhibit similar value and trend. Theoretically, one would expect the SE of thicker sample to give higher SE due to

increase in absorption loss. It is suspected that the SE of the sample is much higher than the SE of the enclosure and the measured SE is practically the SE of the enclosure itself. To prove our suspicion, we replace the sample with a 1 cm thick solid Aluminum as a reference for comparison. The green curve is the measured SE of 1 cm thick solid Aluminum. Interestingly, it resembles all the SE curves of porous Aluminum samples. It is suspected that the EM leakages along the edges of the test jig causing the problem. The mechanical design of the test jig is further improved to ensure better electrical contact between the porous Aluminum test sample and the wall of shielded room. Figure 5.4 shows the improved test jig, where additional L-shape Aluminum plates are added to improve good electrical contact between the conductive gasket and mounting panel.

Figure 5.4 Improved Test Jig Fixtures

With the improvement made on the test jig, the SE for 2 cm thick porous Aluminum sample is measured again and given in Figure 5.5.

Figure 5.5 Measured SE for 2cm Porous Al with New Test Jig

It shows higher SE at lower frequency but not much better at higher frequency. It indicates that the overall SE of the shielded enclosure is the limiting factor for the SE measurement of the porous Aluminum sample. In order to measure the intrinsic SE of the sample, the SE of the shielded enclosure must be much higher than the intrinsic SE of the sample under test. The actual SE of the porous Aluminum samples could be higher than those measured values shown in Figures 5.3 and 5.5

5.2 Shielding Effectiveness Simulation of Alporas

The measurement results in Section 5.1 show that the true intrinsic SE of the porous Aluminum could not be measured due to the limitations of the shielded enclosure. To evaluate the shielding property of the porous Aluminum, a full-wave simulation is carried out using the CST MICROWAVE STUDIO, which is 3D electromagnetic simulation tool. The simulation is done in the frequency range of 100 MHz to 1 GHz.

The conductivity and permeability of the porous Aluminum must first be known before any meaningful electromagnetic simulation. As the relative permeability of Aluminum and air are both equal to unity, the relative permeability of porous Aluminum (mixture of Aluminum and air) is also unity. However, the electrical conductivity does vary with

percentage of porosity. The electrical conductivity measurement of porous Aluminum has been measured in Chapter 4 and its value is found to be 5.887×10^4 S/m.

A shielded box with dimensions $40 \text{ cm} \times 40 \text{ cm} \times 40 \text{ cm}$ is modeled. The material of the box is defined to be Alporas porous Aluminum by specifying the electrical conductivity $= 5.887 \times 10^4$ S/m and permeability $= 4\pi \times 10^{-7}$ H/m. Three electrical field probes are specified at the center of the shielded box, as shown in Figure 5.6. An x-directed incident electric field of 1×10^{10} V/m approaching the box is then defined as the external field source, as indicated in Figure 5.7. Such a high field is chosen because the box is totally enclosed with no holes or slots. After several iterations in simulations, the incident field of 1×10^{10} V/m is chosen to ensure that the probe defined in the box could detect the incident field after it penetrates through the shield barrier.

Figure 5.6 Shielded Box with Probes

Figure 5.7 Shielded Box with Incident Plane Wave

After setting electrical parameters of the material, the full-wave simulation is carried out. In this simulation, probe 1 at x-direction will be monitored for the received field. To be able to simulate the field transient within the wall of the shielded box when the incident field penetrates the shield barrier, the shielded box must be meshed into finer cells. However, increasing mesh cells causes increase in computational time. Hence, only finer local meshing is done within the shield wall, so as to avoid prohibitive computational time. Figure 5.8 shows the meshing details of the local meshed box.

Figure 5.8 Meshing of the Shielded Box

The thickness of the porous Aluminum shielded box is specified as 1 mm. The maximum number of mesh cells in the wall is specified at 8, as higher number of mesh cells leads to prohibitive computational time. The computer used for this simulation has Intel duel CPUs of 3.0 GHz and RAM of 4 GB. Table 5.2 lists the total mesh number and simulation time for different mesh cells in the wall.

Table 5.2 Mesh Number and Simulation Time

Wall Mesh Cells	No. of Time Steps	Total Mesh Number	Simulation Time (Sec)
1	13572	195,112	148
2	18754	216,000	426
3	22183	238,328	829
5	30636	262,144	1527
8	41275	338,171	2428

Figure 5.9 shows the received electric field by the probe within the box with 5 mesh cells in the wall. The difference in the incident field and received field provide the SE performance of the 1 mm thick shielded box.

Figure 5.9 Electric Field Received by the Probe for 5 Mesh Cells in the Wall

Figure 5.10 shows the simulated SE for 1 mm thick porous Aluminum box with 5 meshes and 8 meshes in the wall.

Figure 5.10 Simulated SE of the 1 mm thick Porous Aluminum Shielded Box

Figure 5.10 shows that when the mesh cell number increases to 5, the SE starts to converge, and further increase in mesh cell number, such as 8, does not show much difference in SE. Based on the simulated SE using 5 mesh cells, the simulated SE agrees quite well with the calculated SE given in Table 4.2. Some differences are expected as the calculated SE assumes an infinite wall of material of specific thickness and the simulated SE is for a shielded box. Some drop in the simulated SE at 530 MHz, 838 MHz and 918 MHz are expected due to cavity resonances of the shielded box. The calculated SE does not account for the cavity resonance effect. Anyway, both the simulated and calculated SE does lead to a conclusion that the intrinsic SE of the porous Aluminum (even with more than 90% porosity) is sufficiently high enough for most the shielding applications.

5.3 Construction of Shielded Enclosure and Shielding Measurement

The measurement and simulation results in the previous sections show that porous Aluminum does provide good SE even with high porosity. Hence, the use of porous Aluminum for architectural shielding applications is feasible. To show the feasibility of using such material for architectural shielding purposes, a shielded room is designed and assembled using the Alporas porous Aluminum panels. The overall shielding performance is also measured and presented.

5.3.1 Design and Construction of Shielded Room

A pre-test on the mechanical strength of a porous Aluminum sample is carried out to ensure that mechanical clamping method can be used to join the adjacent pieces of porous Aluminum panels together. The pre-test result is satisfactory and a shielded room is designed using the available panel sizes. Figure 5.11 shows the design drawing of the shielded room to be installed.

Before clamping the porous Aluminum panels, the surfaces of the panels shall be cleaned and buffed to ensure good electrical contact with metal frame. Conductive gaskets are lined along the panel edges to ensure good electrical contact and bolts and nuts spaced at intervals of 2.5 cm are tightened with equal torque with an adjustable torque wrench. After all panels are bolted together, the door is finally installed.

Figure 5.11 Dimensions of Shielded Room

Alporas porous Aluminum panels with two different sizes are fabricated. The sizes and quantity of the panels used are: 8 pieces of 2.400 mm (L) $\times$ 700 mm (W) $\times$ 20 mm (Thickness) panels and 4 pieces of 1500 mm (L) $\times$ 700 mm (W) $\times$ 20 mm (Thickness) panels. The shielded door has a dimension of 1800mm (H) $\times$ 900mm (W). It is the usual shielded door made of steel-wood-steel panel. Figure 5.12 shows the final completed shielded room.

Figure 5.12 Completed Shielded Room

5.3.2 Shielding Performance of the Shielded Room

Table 5.3 lists the equipments used in the test. Two Loop Antennas are used in frequency range 250 kHz to 30 MHz, two Biconical Antennas are employed to cover frequency range of 40 MHz to 200 MHz and two Log Periodic Antennas are chosen for frequency 300 MHz to 1 GHz.

Table 5.3 Instruments for the Measurement

Instrument	Model	Serial No.	Quantity
AFR Signal Generator	2023A	202301-208	1
HP Spectrum Analyzer	8591A	2944U00467	1
ETS Loop Antenna	6509	00062948 88121133	2
EMCO Biconical Antenna	3104	88113821	1

Compliance Design Biconical Antenna	B100	306	1
EMCO Log Periodic Antenna	3146 3147	89012325 91121047	2

Test procedure in Section 3.1.2 is followed. The frequency range covered in this test is from 250 kHz to 1 GHz. The whole frequency range is sub-divided into three frequency bands according to the antennas used in the test (250 kHz to 30 MHz, 40 MHz to 200 MHz, 300 MHz to 1 GHz). A total number of 24 frequencies are measured. These frequencies are: 250 kHz, 500 kHz, 1 MHz, 5 MHz, 10 MHz, 20 MHz, 30 MHz, 40 MHz, 50 MHz, 60 MHz, 70 MHz, 80 MHz, 90 MHz, 100 MHz, 200 MHz, 300 MHz, 400 MHz, 500 MHz, 600 MHz, 700 MHz, 800 MHz, 900 MHz, and 1000 MHz. The SE is measured at the door and the side wall with the antenna oriented in both horizontal and vertical polarizations.

For each type of antenna, reference signal level was established before SE measurement. Without the shield barrier, the reference signal reference level is obtained at 0.6 m for loop antennas, at 1 m for both Biconical antennas and the Log Periodic antennas. The signal generator is set at 13 dBm output level and connected to the transmitting antenna. The received signal is recorded through the spectrum analyzer. Figure 5.13 shows the test setup to obtain the reference signal level without the shield barrier.

Once the reference signal is established, the receiving antenna is placed inside the shielded room and the transmitting antenna is placed outside. Both antennas are adjusted to the same height in the same plane. Figure 5.14 shows the antenna setup for the SE measurement using Biconical antennas (Note: the door is closed during the actual measurement). The SE is measured with antennas placed in horizontal polarization and then measurement is repeated with antennas changed to vertical polarization.

Figure 5.13 Reference Measurement

Figure 5.14 Antenna setup for Shielding Effectiveness Test

Measurement Result

The measured results for the horizontal and vertical polarizations are given in Figure 5.15 and Figure 5.16, respectively.

Figure 5.15 Shielding Effectiveness for Horizontal Polarization

Figure 5.16 Shielding Effectiveness for Vertical Polarization

The results show that the shielded room can achieve SE of between 60 dB and 120 dB. It indicates that with the simple clamping method, shielded room constructed using the porous Aluminum panel is as effective as the conventional metal-wood-metal double shield. However, it can achieve significant weight reduction due to its high porosity. Even with 90% porosity, the panels are rugged enough without cracks during the installation process.

Chapter 6 Conclusion and Future Work

6.1 Conclusion

In this thesis, the feasibility study of using porous Aluminum for electromagnetic shielding application has been completed. The thesis begins with an overview of the fabrication techniques and mechanical property of porous Aluminum. A simple and yet reliable measurement method has been proposed so that the conductivity of the porous Aluminum can be measured with good confidence. In addition to full-wave simulation of a shielded box, a shielded room using porous Aluminum panels with 90% porosity has been assembled and tested. With the measurement result, it was found that using porous Aluminum for shielding applications is feasible. With its light weight property and adequate shielding performance, porous Aluminum is attractive for large scale shielding of existing buildings, where structural loading is a concern. The additional desirable properties, such as sound absorption and fire-resistant, make it a good material to fulfill many functions in building construction.

6.2 Further Work

Future work that worth exploring are as follows:

- A more comprehensive study on mechanical and electrical properties of porous metals with varying porosity should be carried out;
- The mechanical joining techniques suitable for porous metal panels should be studied so as to improve the shielding integrity along the joints the enclosure to meet more stringent shielding specifications; and
- Graded porous material with various layers of different porosities should also be studied as such material could tailor a wide variety of functions to meet the users' requirements.

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List of Publications

- [1] K.Y. See, Y. Ling, W.J. Koh, J. Ma and S.F. Ho “Feasibility Study of Using Porous Metal as Practical Shielding Material”, Proceeding of Asia-Pacific Symposium on Electromagnetic Compatibility and 19th International Zurich Symposium on Electromagnetic Compatibility, May 2008, pp. 451-454.

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