Scientific Journal of the Military University of Land Forces
ISSN: 2544-7122 (print), 2545-0719 (online)
2020, Volume 52, Number 4(198), Pages 931-946
DOI: 10.5604/01.3001.0014.6064

Original article

A review of the radar absorber material and structures

Ayhan Aytaç*, Hüseyin İpek, Kadir Aztekin, Emre Aytav, Burak Çanakçı

Mechanical Engineering Department,
National Defense University's Turkish Military Academy, Ankara, Turkey,
e-mail: aytac@kho.edu.tr; hipek@kho.edu.tr; kaztekin@kho.edu.tr; eaytav@kho.edu.tr; bcanakci@kho.edu.tr

INFORMATION

Article history:
Submited: 14 November 2019
Accepted: 17 February 2020
Published: 15 December 2020

ABSTRACT

The development of technologies that can rival the devices used by other countries in the defense industry, and more importantly, can disable their devices is becoming more critical. Radar absorber materials (RAM) make the detection of the material on the radar difficult because of absorbing a part of the electromagnetic wave sent by the radar. Considering that radar is one of the most important technologies used in the defense industry, the production of non-radar materials is vital for all countries in the world. Covering a gun platform with radar absorber material reduces the radar-cross-sectional area (RCA) value representing the visibility of that platform on the radar. This review aims to present the electromagnetic principles and developed Radar Absorbent Materials (RAM) during decades from the 1960s. The frequency range 8-12 GHz in the electromagnetic spectrum is named the microwave region and used in airport radar applications. Revised basis of electromagnetic theory and defined by a variety of absorbent materials and some design classification types and techniques are described in this article.

KEYWORDS

radar absorber, wavelength absorber, lossy dielectric, shape factor

* Corresponding author

Introduction

Radar, an acronym for "radio detection and ranging", is an object detection system [1]. For detection purposes, through the electromagnetic (EM) spectrum, ultraviolet, visible, infrared, microwave, and radio frequencies can be used in these systems. These electromagnetic waves are used to determine the range, altitude, direction, or speed of objects [2].

It is accepted that the first application (or studies) of the radar absorber materials started during World War II by Germans [3]. In general, military and civil applications need to preventing EM or microwave reflection [4-9]. At present, the radar absorbing materials (RAM) applications spans are very common, and the applications can be seen below [3; 10, Chapter 16]:

Aerospace and aeronautics

The power of nations is measured by economic conditions and the ability of military vehicles they own. Moreover, vehicle abilities (especially aircraft and space crafts) could be expressed as the durability of joints, high strength component, mobility, and invisibility on the radar screen. The invisibility of the aerospace and aeronautics is a critical component for the RAM applications due to the requirements of lightweight and mobility [11, p. 241-64].

EM protection from natural phenomena and intentional interference

Many electronic devices with increasing demand and use are sensitive to EM signals. Therefore, most medical or electronic studies should be protected by RAMs. Some of the devices could be protected from EM signals easily with a web system as Faraday's cage, but some of the devices or studies need a more complex protection system as RAM [12].

High-intensity radiated fields (HIRF) protection

Developing avionic systems turn into the electronic and electro-mechanical system from the mechanic or analog ones. This transformation was safer than the mechanical one. However, the transformation came with the problem of "lightning and high-intensity radiated fields". These problems could affect the aircraft-flight-safety and may cause losses in aircraft and life [13, 14].

Nuclear physics, nuclear EM pulses (NEMP) protection and shields adopted in particle accelerators

The study of nuclear physics also needs EM protection not only to measure the system outputs but also to protect the electronic parts of the vehicles. This is because nuclear explosions cause lightning and electromagnetic pulses [13, 15].

Electromagnetic compatibility (EMC)

Electromagnetic compatibility (EMC) is another important chapter. Developing technology allows controlling the system remotely. If the EMC protection of the systems ignored new designed electronic system would not work or could cause some accidents or chaos. In other words, systems should be designed electromagnetically compatible with EM [16].

Equipment-level shielding

It could not be possible or necessary to protect the system from EM signals. Then equipment-level protection could be a solution against the EM signals by protecting the EM-sensitive part [17].

Anechoic chambers for the realizations of wedges and pyramidal arrays

Anechoic chambers have been used to determine some properties of the electronic devices from digital device manufacturers. Furthermore, scientists use the anechoic chambers to investigate the sound wave at a free-space condition [18].

Human exposure mitigation

Direct or indirect protection techniques could be applied against the different EM signals (EM source) but the EM shield systems' most important task is human protection, basically. Developing of the electronical devices, from mobile phone to radio, effects human and animal life's and the protection from the EM signals plays a key role [19].

The frequency of the EM spectrum range 8-12 GHz is named microwave region and uses in radar applications. Radar Cross Section (RCS) is a measure of how detectable an object is with radar, and a larger RCS indicates that an object is more easily detected. RAM reduces the EM energy reflected the radar employing absorption, thence RCS diminishes. RAM's technique is based on lossy characteristics of dielectric or magnetic materials that present the appropriate impedance matching or attenuates the radar wave once it enters the material [20, 21].

A few critical cases could control the surface response of microwave radiation. For example, a microwave anechoic cellular in a body of limited space in order to purpose to simulate the wall should not be reflected by lining formed by electromagnetically absorbent material [22].

The subject of the radar absorber systems can be classified into two leading groups: a) shape factor of the radar absorber surface (surface geometry) and b) materials. A general classification can be seen in Figure 1.

This review article aims to provide brief information about the methods used in numerous scientific studies conducted so far. In the selected references, the very basis of the study results has been mentioned, and a general RAM review article has been prepared. It aims at guiding the new studies to be carried out.

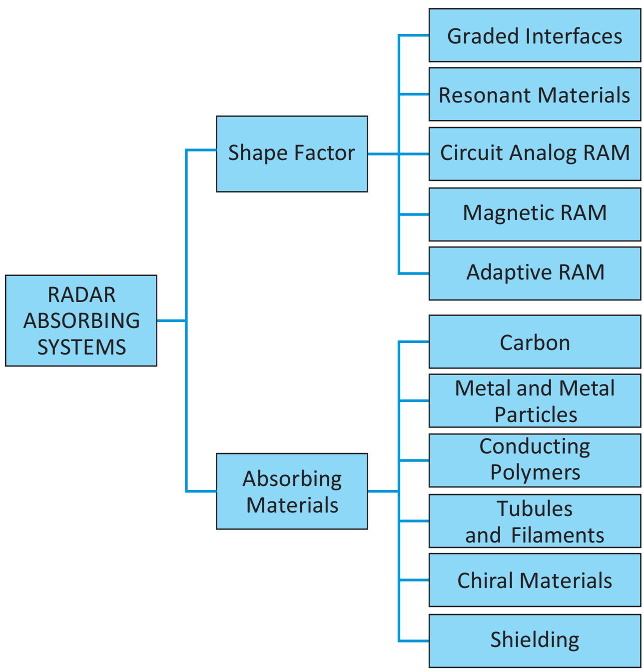

Fig. 1. Classification of the radar absorber
Source: [23].

1. Shape Factor of the RAM

1.1. Graded Materials

Graded materials are designed for a specific purpose. For example, armor could be produced form a functionally graded material or a radar wave absorber. Step changes the wave characteristic between the sections [24].

Transformers the broadband characteristics can be addressed by adding an infinite number of discrete sections. Similarly, a narrow band resonant absorber, by adding multilayer form or tapering shape converted into a broadband absorber [25].

Variable would feature dielectric multilayer structures if the impedance of each sequential layer kept smooth broadband that ensures compelling features. These features improve the passage of successive waves of each layer and are formed in smaller reflections from the interface of layers. The fluctuation is reflected in an unlimited number of layers in the multilayer absorbent, and the loss of their energy before reaching the reflective wall. Microwave signals are converted into heat due to the structure of the absorber [24]. Heat transfer mechanisms can also dissipate this heat. Figure 2 shows the graded coating of the multilayer.

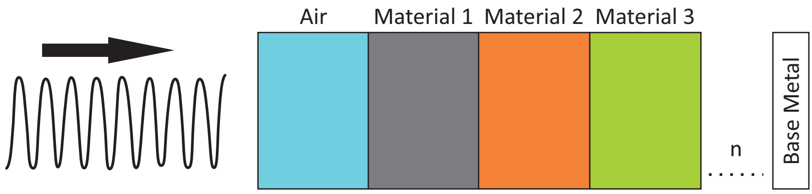

Fig. 2. Multi-layered structure of the graded material
Source: [2].

1.1.1. Pyramidal Absorbers

Most radar-absorbing materials (RAMs) are designed according to the dielectric of the loss in the form of a sharp geometry (e.g., pyramid form). This designed form is fixed alongside the root of a continual panel of the lossy dielectric. This design reduces passage through the wave impedance of the case environment to the dielectric of the loss that the panel and decreases the reflection of the wave. The RF waves progressed into the pyramidal structure are absorbed by the lossy dielectric layer at the RAM base. The working principle of this condition is the same as of impedance matching, which is the sharp profile of the transmission line. This impedance changing just works in normal proportions. If illumination of the structure over 30° angles, a considerable reflection occurs when a lossy dielectric solid piece of the wave “sees” the RAM. Most of these designs are unique, and most information about the systems is the RAM manufacturers’ property [26]. Figure 3 shows the schematic of the pyramidal absorber.

1.1.2. Conical (Tapered) Loading Absorbers

The conical absorber is a typical plate structure combined with a lossy material and low loss substance. The lossy piece is scattered homogenous and parallel with a vertical to the surface and proceeds into the substance. It is challenging to produce this type of material. Since

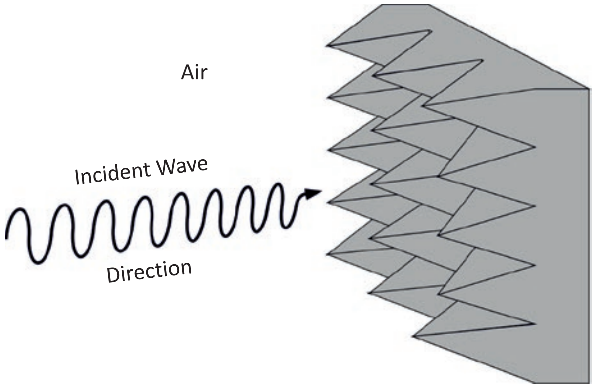

Fig. 3. Schematic of the pyramidal absorber
Source: [2].

adjusting the gradient is essential, it is not easy work. These materials are much thinner than the pyramidal absorbers, it could provide the advantage, but the absorbance performances are more unsatisfactory [2]. Figure 4 gives the tapered loading absorbers graphs.

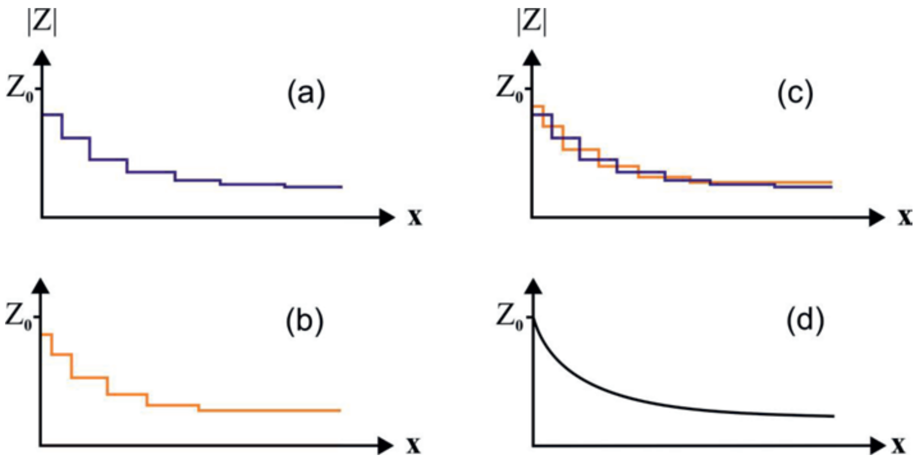

Fig. 4. a) Tapered loading absorber and b) stepped type c) combination of a and b d) smooth type
Source: [2].

1.1.3. Matching Layer Absorbers

The matching layer absorbers can be used for gradual transition materials to eliminate the thickness problems of the absorbing materials. The transition matching layer is between the event and the suction medium. The layer thickness and impedance rate of the transition layers are significant. These rates are compared with the two impedances (i.e., the absorbent and event environment). It is rational to balance the impedance of the event environment with the combined impedance from the first and second layers. If the matching layer thickness is one-quarter of a radiation wavelength in the layer, then matching occurs, and the following equation could be used:

$$Z_2=\sqrt{Z_1 \times Z_3} \quad (1)$$

where:

Z_1 is the impedance of the environment, Z_2 is the impedance of the matching layer, Z_3 is the impedance of the absorbing layer.

If the frequency of the wave is equal to the optical thickness of the structure, impedance matching can be seen. Because of this condition, it is limited that the band absorbent of the matching layer materials. In the microwave frequency range, these absorbents are produced with an intermediate impedance and one-fourth thickness of the wavelength for absorbing the wave energy [2]. A schematic matching layer absorber is given in Figure 5.

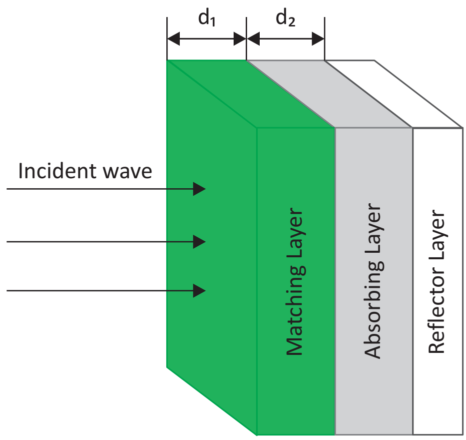

Fig. 5. Schematic of the Matching Layer Absorbers
Source: [27].

Where d_1 represents the matching layer thickness, and d_2 represents the absorbing layer thickness.

1.2. Resonant Materials

Resonant materials include Dallenbach Layers, Salisbury Screen, and Jaumann Layers or one-fourth wavelength absorbents. The impedance is not compared between the event and absorbent medium, and the material is thin, so all the wave energy cannot be absorbed in this material class. This case has consequences on the reflection and transmission at the initial interface of the layers. The returning wave from the surface is the reversal of π (half period of the wave). According to the absorbent environment, the transmitted wave travels and is reflected from the metal surface. This transmitted wave undergoes total reflection and propagates back through the front face of the absorber. This second reflection is also consequent with the changing of the wave behavior, precisely a reversal of the π before turning back from the surface of the wave to the case environment. If the linear span traveled by the transmitted wave is 1/2 of wavelengths or folds, the reflection of the two waves will be out of phase. If the size of the two returning waves is the same, the total reflection volume will be zero [23].

In Dallenbach's absorber, no resistive sheets are used, and the incident power is dissipated in lossy homogenous dielectric materials layered on top of each other over a ground plane.

Dallenbach Layers was developed based on ferrite materials and patented. The use of two or more layers with different absorbent bands will expand the absorption bandwidth. The bandwidth of standard ferrite absorbers has been improved through a two-layer absorber design with a ferrite layer (air-absorber interface) and short metal fibers (absorber-metal interface) [28]. Figure 6 shows the Dallenbach Layers.

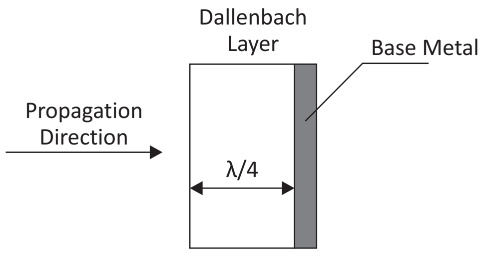

Fig. 6. Dallenbach Layer
Source: [28].

The Salisbury Screen is an inactive radar-absorbent metal ground plane, i.e., a thin resistive sheet placed with a distance of λ/4 above. At resonance, the conducting layer short circuit impedance is transformed into an open circuit at the resistive sheet position, usually 377 Ω/square. Thus, the structure presents a perfect impedance match to free space at one frequency, and strongly absorbs the incident layer waves. The maximum –10 dB reflectivity bandwidth of 77% at a typical ratio is obtained when the permittivity of the inter-laminar of material is $\varepsilon r=1$ [29]. Figure 7 shows the principles of the Salisbury Screen.

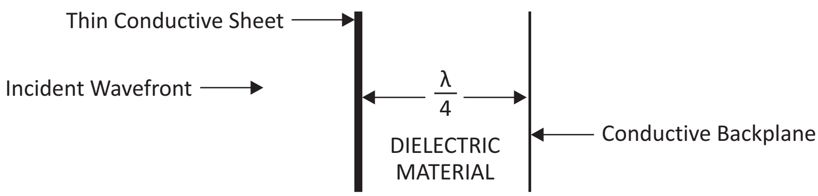

Fig. 7. Salisbury screen
Source: [30].

1.3. Circuit Analog RAM

Circuit Analog (CA) RAMs are low-loss material sheets on which specific conductive models have been accumulated. The models form the resistance, inductance, and capacitance. The accumulated film layer can be indicated by an equivalent RLC circuit, the parameters of which can be controlled by the geometric format, film thickness, and conductivity of the accumulation of the film. An example of a model accumulated on a CA layer is shown in Figure 8. CA absorbent can be tuned, as with an RLC circuit, enabling the designer to develop the bandwidth of the multi-layer form. Commonly, CA absorbent material is a lossy version of a class of printed models known as frequency selective surfaces (FSS) [31].

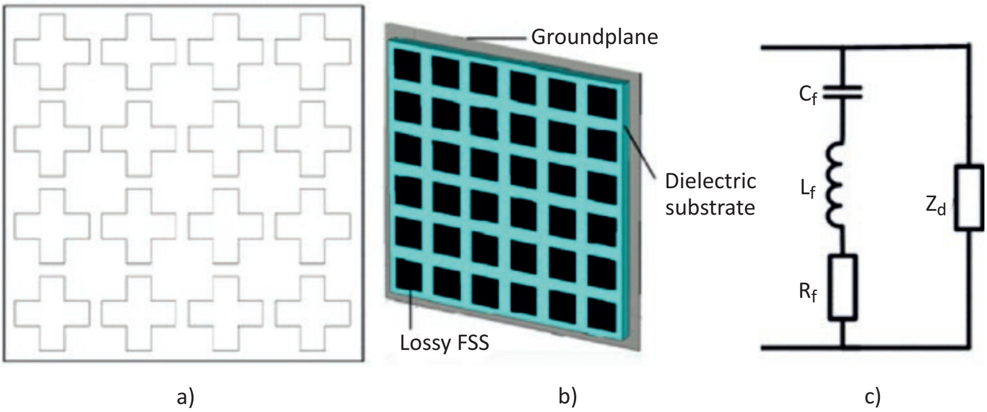

Fig. 8. Circuit analog RAM: a) cross-section of the analog circuit, b) three-dimensional sketch, c) equivalent circuit
Source: [32-35].

1.4. Magnetic RAM

The losses in the magnetic absorbent materials are due to the existence of carbonyl iron or ferrites dispersed in the caoutchouc matrix. The small dipoles contained in the magnetic absorbent materials divert them depending on the environment. When the field changes quickly, the dipoles delay the impressed magnetic field, torque is enforced, and in this way, the material energy is distributed. Most of the magnetic RAMs utilize ferrites as the distributing element. Every ferrite particle has two suitable frequencies and thicknesses, which are associated with a material constant. The ferrite is chosen in such a way that the initially fit periodicity encounters with the operating requirements. The initial fitting thickness is free of the periodicity. However, usually, 8 micrometers thickness is applied. The mechanism of the magnetization that occurs is caused by the ferrite odd typical feature. There are three mechanisms for magnetization that are available for the ferrite particles. These are the relaxation magnetization, the magnetic field resonance behavior, and the movement of rotation resonance. The first one of these mechanisms is predominant for the EM absorption [35]. If the environment temperature reaches the Curie temperature, the disintegration tendency of the magnetic RAMs breaks down, thus causing the corruption of the magnetic property. Even though the ceramic ferrites can be used at temperatures higher than Curie temperature, there is a restriction. They can be used up to the upper-frequency boundary [35].

1.5. Adaptive RAM (Dynamically Adaptive – DARAM)

Conventional (i.e., passive) radar absorbing materials (RAMs) has been used for no more than 50 years. However, to use dynamically adaptive RAM (DARAM), it took a little longer for the material technology to develop appropriately. Furthermore, it can be seen an extremely useful in several camouflage and deception roles, mostly if the RAM response time can be made sufficiently short. However, for DARAM to be integrated effectively into an electronic warfare system, a method is required to have it confirmed. For the confirmation of the integrated system correctly, reflectivity null in the DARAM's frequency response should be 'steered' onto an enemy radar frequency [36]. In practice, it does not need to be an excellent microwave reflector for precise null reflectivity. This condition may be verified by considering a RAM structure consisting of two resistive sheets [37]. This technic is similar to CA materials where the capacitance and resistance of the impedance sheet can be adjusted [23].

2. Absorbing Materials

2.1. Carbon

Carbon is an essential element, and it is one of the first absorbent materials due to its low conductivity [32]. Carbon nanostructures have excellent properties for RAMs. Graphite, carbon nanotubes (single or multi-layered), fiber, and carbon black are the most frequently utilized ones [38-42]. These are microwave-lossy materials that describe an electrical permittivity. Moreover, these materials have a specific electric field with a complicated amount [43].

According to the complex permittivity theory, when an EM field spreads in a dielectric material, two electrical effects occur. One of the types is conduction, and the other one is displacement current. The influence of conducting current causes an increase in power loss. The power loss is concerned with virtual permittivity. The interaction with the position changing the current induces the polarization affected by the described real permittivity. Therefore, an increase in the real part of the complex permittivity can be mainly referred to as dielectric pull-off and the area of the polarization effect. In contrast, an increase in the virtual part of the complex permittivity can be connected to the increasing electrical conductivity of the material [44]. In general, carbon-based absorbents tend to have very low densities. Their mixing proportions are meager in comparison with those of the magnetic absorbents. They require more thickness to be resonant in radar wave frequencies [31].

2.2. Metal and Metal Particles

The shielding and/or absorbing of the EM should be noted in the field to ensure a satisfactory result for the Electromagnetic Interference (EMI) problems. Rubber radar absorbing material (RRAM) is useful as a shielding material. RRAM can decrease or weaken EMI in away. The RRAM composites are made of rubber as a matrix with EM wave absorbent materials and serve mainly as reinforcement. The reinforcements provide the EM performance of the radar absorbents. Besides, the matrix provides a soft and flexible body. RRAM can be used at a varying temperature range. Thus, the reinforcements should be useful at different temperatures range. In other words, the reinforcement phase should be required to possess high Curie temperature and good temperature stabilization. The reinforcements possessing high magnetization would have high permeability. Hence, the higher permeability positively affects the microwave absorbing of the RRAM [45]. One of the most used reinforcement materials of the RRAM is the carbonyl iron. Carbonyl iron can be applied for microwave absorbent elements as a reinforcement in the frequency range of 2.6-18 GHz and even higher. That is because it has a high Curie temperature, the higher specific saturation magnetization intensity [45], and the high value of microwave permeability and dielectric constant. Therefore, carbonyl iron is widely used in EM protection and absorbent materials [46]. As a synthetic rubber, Ethylene-Propylene-Diene Monomer (EPDM) has excellent wear resistance, aging resistance, and chemical resistance. Furthermore, EPDM has excellent compatibility with many kinds of reinforcement materials. So, it is favorable to be the material of the RRMA.

Furthermore, carbonyl iron particle size can be less than 10 microns, and such reinforced material would increase the durability of the composite. The structure of the RRMA is supported by a conducting plate and a radar-absorbent materials substrate to achieve the EM wave absorption [47].

Another material group is ferrites. Moreover, iron oxides have an extensive range of electrical and magnetic properties. The most regular class is spinel ferrites. This ferrite group has a cubic crystal structure and can be represented with the general formula of MFe_2O_4. Another class usually contains sizeable divalent metal ions such as Ba, Sr, Ca, or Pb, which crystallizes into a hexagonal structure [22].

2.3. Conducting Polymers

In a polymer, the formation of polarons and bipolarons makes the polymer conducting. Local oxidation of the polymer causes this condition, and the polypyrrole (PPy) is one example. The polymer conductivity can be shown by phonon-assistance by randomly jumping off the separated regional conditions [23]. Nevertheless, the polymers have inherent problems as typically severe behaviors. Some of them can be enforced into shapes due to their natural behaviors, such as polyaniline (PANI).

Production of the thermoplastic composites is a different method. For example, making a composite of the PPy, the interface of PVA and PVC should be polymerized simultaneously. Alternatively, an emulsion polymerization can also be used. Another example, PANI, can be soluble in some kinds of solvents, or some chemical treatments can increase the solubility of monomers. Nevertheless, these kinds of treatments generally decrease conductivity. Coating the polymers (especially textile materials) again another conductive polymer production method. Substrates materials are applied as a base, and the treatment of the oxidants absorption and then exposing them to monomer makes them conductive [23].

2.4. Tubules and Filaments

Radar absorber structures (RAS) have become a popular research area using fiber-reinforced composite studies today [48]. With the addition of the EM powder into the composite matrix, it is possible to convert the fiber-reinforced polymeric composites to the EM structure. This method is a logical and relatively simple way to produce a RAS. Furthermore, it could be achieved by adjusting the electric property (complex permittivity) or magnetic property (complex permeability) of material. Also, the concept of wideband can be applied to style the composite radar absorbing structures. The absorbing structures can be made with scattered EM waves due to phase cancellation and impedance matching known as multilayer Jaumann's absorber structure. Jaumann's-type radar absorber is formed from many resistive sheets, low-loss, and low-permittivity spacers. To split those sheets and a conducting backup plate [49], polymeric composites with low-loss and low-permittivity can be used. These composite structures serve as spacers matching the electrical requirements of the absorber [50].

2.5. Chiral Materials

Artificial chiral structures are defined as changing the plane of polarization. There were researchers in the first half of the twentieth century who studied various human-made materials. In the 1950s, the materials with artificial dielectric properties started to be investigated for light-weight microwave antenna practices. The attention of the study of artificial chiral materials came up prominent again in the 1980s, and researchers were studied for microwave radar-absorbing for stealth applications. As for Veselago's theoretical prediction [51], constitutive parameters such as the permeability of artificial materials are relatively complex. When EM waves in chiral materials, the orientation of the spread vector is in the left direction, while in conventional materials spread vector is towards the right. Therefore, such materials are also known as left-handed materials (LHMs) or meta-materials. Due to its unique features, LHMs have been favored by military departments for potential applications in stealth technology and various other unmilitary applications [52].

2.6. Shielding

In recent years, the safeguard application of EM waves continues to attract high interest for commercial and military purposes. EM safeguard application refers to reflecting the wave and/or absorption of EM radiation by a material. Thereby, it acts as a shield against the penetration of the radiation through materials [53].

Composites with high electrical conductivity and dielectric constant bring development possibilities to custom metal for EM attempt safeguard feature. Nanomaterials (especially nanocomposites) show perfect EM attempt safeguard performance with larger frequency bandwidth, better compatibility, and lower overall mass. Consequently, nanocomposites have turned out to be the best possible candidate for EM attempt safeguard covering centimeter and millimeter bands [44, 54-56].

Conclusion

Investigation and development of the radar absorber materials have been studied since World War II, especially in the military. With the advancing radar technology, a parallel direction has also evolved in the studies on hiding from radar. Radar technology is based on the sent and received microwaves. Nowadays, radar absorber materials and structures have been studied not only for military purposes but also for protection from harmful microwave and EM waves. As a result, the papers investigated that radar absorber materials evolved with time. The results obtained from the literature review are compiled and summarized below.

- Multilayer structures with variable dielectric properties provide very effective broadband properties if the impedance of each successive layer is kept smooth.
- Most of the radar-absorbing materials (RAMs) are designed using a lossy dielectric material in the form of pyramids, mounted side-by-side, and connected to the base, forming a continuous lossy dielectric sheet.
- The use of two or more layers with different absorption bands will increase the bandwidth absorption.
- Carbon-based absorbers generally tend to have very low densities, and the mixing ratios are very low compared to those of magnetic absorbers. These materials are microwave loss materials that define the interaction of a material with an electric field and are generally characterized by an elaborate amount of electrical conductivity.
- The RAM is mainly made of rubber matrix and EM wave absorber fillers. The fillers provide the necessary EM performance of the radar-absorbing material.

– The construction of polymeric composite radar absorber structures can be achieved by regulating the electrical property (complex permeability) or magnetic property (complex permeability) of the material.
– Nanocomposites are the best potential candidates for EM interference protection.

Acknowledgement

No acknowledgement and potential founding was reported by the authors.

Conflict of interests

All authors declared no conflict of interests.

Author contributions

All authors contributed to the interpretation of results and writing of the paper. All authors read and approved the final manuscript.

Ethical statement

The research complies with all national and international ethical requirements.

ORCID

Ayhan Aytaç https://orcid.org/0000-0002-7963-0640

Hüseyin İpek https://orcid.org/0000-0003-0835-2978

Kadir Aztekin https://orcid.org/0000-0002-6323-9401

Emre Aytav https://orcid.org/0000-0003-4296-6703

Burak Çanakçi https://orcid.org/0000-0002-6093-3107

References

1. Seo IS, Chin WS, Lee DG. *Characterization of electromagnetic properties of polymeric composite materials with free space method.* Composite Structures. 2004;66(1):533-42.
2. Yaman MD. *Thin film coating of glass fabrics for radar absorbing composites*. Unpublished master's thesis. İzmir, Turkey: İzmir Institute of Technology; 2015.
3. Micheli D et al. *Synthesis and electromagnetic characterization of frequency selective radar absorbing materials using carbon nanopowders.* Carbon. 2014;77:756-74.
4. Pinho MS et al. *Performance of radar absorbing materials by waveguide measurements for X- and Ku-band frequencies.* European Polymer Journal. 2002;38(11):2321-7.
5. Fan Z et al. *Electromagnetic and microwave absorbing properties of multi-walled carbon nanotubes/polymer composites.* Materials Science and Engineering: B. 2006;132(1):85-9.
6. Wu M et al. *Electromagnetic and microwave absorbing properties of iron fibre-epoxy resin composites.* Journal of Physics D: Applied Physics. 2000;33(19):2398-401.
7. Park K-Y et al. *Fabrication and electromagnetic characteristics of electromagnetic wave absorbing sandwich structures.* Composites Science and Technology. 2006;66(3):576-84.
8. Peng Z-H et al. *Strong fluctuation theory for effective electromagnetic parameters of fiber fabric radar absorbing materials.* Materials & Design. 2004;25(5):379-84.
9. Oh J-H et al. *Design of radar absorbing structures using glass/epoxy composite containing carbon black in X-band frequency ranges.* Composites Part B: Engineering. 2004;35(1):49-56.

10. Reddy B. *Advances in Nanocomposites: Synthesis, Characterization and Industrial Applications*. IntechOpen; 2011.
11. Joshi M, Chatterjee U. *8-Polymer nanocomposite: An advanced material for aerospace applications*. In: Rana S, Fangueiro R (eds.). *Advanced Composite Materials for Aerospace Engineering*. Cambridge: Woodhead Publishing; 2016.
12. Abbasi H, Antunes M, Velasco JI. *Recent advances in carbon-based polymer nanocomposites for electromagnetic interference shielding.* Progress in Materials Science. 2019;103:319-73.
13. Shooman ML. *A study of occurrence rates of electromagnetic interference (EMI) to aircraft with a focus on HIRF (external) high intensity radiated fields*. In: *NASA contractor report 194895*. Hampton, Virginia: National Aeronautics and Space Administration Langley Research Center; 1994.
14. Vogel MH. *Impact of lightning and high-intensity radiated fields on cables in aircraft.* IEEE Electromagnetic Compatibility Magazine. 2014;3(2):56-61.
15. Deb GK, Pande DC. *Nuclear Electromagnetic Pulse (NEMP) – A Threat to Electronics.* IETE Technical Review. 1987;4(1):9-19.
16. Maddocks A. *23-Electromagnetic Compatibility*, In: Laughton MA, Warne DJ (eds.). *Electrical Engineer's Reference Book*. 16th Ed. Oxford: Newnes; 2003, p. 23-1-23-16.
17. Chang C et al. *New Package Scheme of a 2.5-Gb/s Plastic Transceiver Module Employing Multiwall Nanotubes for Low Electromagnetic Interference.* IEEE Journal of Selected Topics in Quantum Electronics. 2006;12(5):1025-32.
18. Holloway CL et al. *Comparison of electromagnetic absorber used in anechoic and semi-anechoic chambers for emissions and immunity testing of digital devices.* IEEE Transactions on Electromagnetic Compatibility. 1997;39(1):33-47.
19. Bogush V et al. *Novel Composite Shielding Materials for Supression of Microwave Radiation*. In: *International Conference on Microwaves, Radar and Wireless Communications, 2006. MIKON 2006*. IEEE/Institute of Electrical and Electronics Engineers Incorporated; 2006.
20. Ertuş EB. *Production, Characterization and Industrial Applications of Radar Absorbing Materials*. PhD Thesis. Graduate School of Natural and Applied Sciences of Dokuz Eylül University. 2014.
21. Neo CP, Varadan VK. *Optimization of carbon fiber composite for microwave absorber.* IEEE Transactions on Electromagnetic Compatibility. 2004;46(1):102-6.
22. Lederer PG. *An Introduction to Radar Absorbent Materials (RAM)*. London; 1986.
23. Saville P. *Review of Radar Absorbing Materials*. Canada; 2005.
24. Iqbal MN et al. *A Study of the EMC Performance of a Graded-Impedance, Microwave, Rice-Husk Absorber.* Progress In Electromagnetics Research. 2012;(131):19-44.
25. Pozar DM. *Microwave Engineering*. New Delhi: Wiley India; 2017.
26. Tong XC. *Advanced Materials and Design for Electromagnetic Interference Shielding*. CRC Press; 2016.
27. Perini J, Cohen LS. *Design of Broad-Band Radar-Absorbing Materials for Large Angles of Incidence.* Ieee Transactions on Electromagnetic Compatibility. 1993;35(2):223-30.
28. Xu FF et al. *Microwave absorbing properties and structural design of microwave absorbers based on polyaniline and polyaniline/magnetite nanocomposite.* Journal of Magnetism and Magnetic Materials. 2015;374:311-6.
29. Rupinder Kaur GDA. *Review on Microwave Absorbing Material using Different Carbon Composites.* International Journal of Engineering Research & Technology (IJERT). 2014;3(5).
30. Seman FC, Cahill R. *Performance Enhancement of Salisbury Screen Absorber Using Resistively Loaded Spiral Fss.* Microwave and Optical Technology Letters. 2011;53(7):1538-41.
31. *Salisbury Screen*, [online]. Available at: http://arc-tech.com/salisbury-screen/ [Accessed: 2 January 2019].
32. Barton DK, Leonov SA. *Radar Technology Encyclopedia*. Artech House: 1999.

33. Knott EF, Schaeffer JF, Tulley MT. *Radar Cross Section*. Institution of Engineering and Technology: 2004.
34. Bhattacharyya A. *Electromagnetic Fields in Multilayered Structures: Theory and Applications*. Artech House: 1994.
35. Sun LK et al. *Broadband metamaterial absorber based on coupling resistive frequency selective surface.* Optics Express. 2012;20(4):4675-80.
36. Vinoy KJ, Jha RM. *Trends in radar absorbing materials technology.* Sadhana-Academy Proceedings in Engineering Sciences. 1995;20:815-50.
37. Chambers B. *Internal monitoring of the frequency response of a dynamically adaptive radar absorbing material.* Electronics Letters. 1996;32(18):1711-2.
38. Singh VK et al. *Microwave absorbing properties of a thermally reduced graphene oxide/nitrile butadiene rubber composite.* Carbon. 2012;50(6):2202-8.
39. Moglie F et al. *Electromagnetic shielding performance of carbon foams.* Carbon. 2012;50(5):1972-80.
40. Wang GZ et al. *Microwave Absorption Properties of Carbon Nanocoils Coated with Highly Controlled Magnetic Materials by Atomic Layer Deposition.* Acs Nano. 2012;6(12):11009-17.
41. Wang T et al. *Synthesis and microwave absorption properties of Fe-C nanofibers by electrospinning with disperse Fe nanoparticles parceled by carbon.* Carbon. 2014;74:312-8.
42. Fan ZJ et al. *Electromagnetic and microwave absorbing properties of multi-walled carbon nanotubes/polymer composites.* Materials Science and Engineering B-Solid State Materials for Advanced Technology. 2006;132(1-2):85-9.
43. Kangal S. *Development of Radar-Absorbing Composite Structures*. Master's Thesis. Graduate School of Engineering and Sciences of İzmir Institute of Technology. İzmir, Turkey: İzmir Institute of Technology; 2013.
44. Micheli D et al. *X-Band microwave characterization of carbon-based nanocomposite material, absorption capability comparison and RAS design simulation.* Composites Science and Technology. 2010;70(2):400-9.
45. Feng YB et al. *Electromagnetic and absorption properties of carbonyl iron/rubber radar absorbing materials.* Ieee Transactions on Magnetics. 2006;42(3):363-8.
46. Pinho MS et al. *Aging effect on the reflectivity measurements of polychloroprene matrices containing carbon black and carbonyl-iron powder.* Polymer Degradation and Stability. 2001;73(1):1-5.
47. Naito Y, Suetake K. *Application of Ferrite to Electromagnetic Wave Absorber and Its Characteristics.* Ieee Transactions on Microwave Theory and Techniques. 1971;Mt19(1):65-&.
48. Fang ZG et al. *Investigation of carbon foams as microwave absorber: Numerical prediction and experimental validation.* Carbon. 2006;44(15):3368-70.
49. Chambers B, Tennant A. *Optimised design of Jaumann radar absorbing materials using a genetic algorithm.* Iee Proceedings-Radar Sonar and Navigation. 1996;143(1):23-30.
50. Zhang Z et al. *Fabrication and optimization of radar absorbing structures composed of glass/carbon fibers/epoxy laminate composites filled with carbon nanotubes*. In: *2008 Conference on Optoelectronic and Microelectronic Materials and Devices*. Sydney, NSW, Australia: IEEE; 2008, p. 209-12. DOI: 10.1109/COMMAD.2008.4802128.
51. Veselago VG. *The Electrodynamics of Substances with Simultaneously Negative Values of permittivity and permeability.* Soviet Physics Uspekhi. 1968;10:509.
52. Dubey A, Shami TC. *Metamaterials in Electromagnetic Wave Absorbers.* Defence Science Journal. 2012;62(4):261-8.
53. Chung B, Cho J. *TVT Folding Technique in Patients with Failed Stress Urinary Incontinence after TVT Procedure.* Journal of the Korean Continence Society. 2001;5.
54. Park KY et al. *Fabrication and electromagnetic characteristics of microwave absorbers containing carbon nanofibers and NiFe particles.* Composites Science and Technology. 2009;69(7-8):1271-8.

55. Cao J et al. *Fabrication, characterization and application in electromagnetic wave absorption of flower-like ZnO/Fe_3O_4 nanocomposites.* Materials Science and Engineering B-Advanced Functional Solid-State Materials. 2010;175(1):56-9.

56. Liu YJ et al. *EMI shielding performance of nanocomposites with MWCNTs, nanosized Fe_3O_4 and Fe.* Composites Part B-Engineering. 2014;63:34-40.

Biographical note

Ayhan Aytaç – Col., Asst. Prof. Ph.D., graduated from Technical Military High School in 1990. He studied at Gazi Technical Educational University for the Turkish Land Forces. He received his MSc and Ph.D. from the Mechanical Engineering Department in 2004 and 2012. Between 1994 and 2005, he worked as a lecturer at the Non-commissioned Officer Vocational School in Balıkesir. Between 2005 and 2013, he worked as a planning officer at the Turkish Military Academy. From 2013 to 2016, he served as Doctrine Officer at the Turkish Land Forces Aviation School. Since 2016, he continues to work as Head of the Mechanical Engineering Department at the National Defense University/Turkish Military Academy. He is the author of studies and publications on machinability, ballistics, surface engineering, and statistical test methods.

Hüseyin İpek – Ph.D., graduated from the Afyon Kocatepe University as a "Technical Teacher" in 2008. He received his MS and Ph.D. degrees from Karadeniz Technical University as "Metallurgical and Materials Engineer" in 2011 and 2017. He held a research assistant position during MS and Ph.D. studies at the Karadeniz Technical University. He worked as a lecturer in the Mechanical Engineering Department at the National Defense University's Turkish Military Academy in the 2018-2019 education period. He has researched polymer-based composite materials, metal-based composite materials, tribology, and additive manufacturing (3D printing) topics.

Kadir Aztekin – Lt. Col., Asst. Prof. Ph.D., graduated from the Military High School in 1996. He studied at the Gazi Technical Educational University for the Turkish Land Forces. He received his MSc and Ph.D. degrees at the Mechanical Engineering Department in 2004 and 2010. Between 2000 and 2014, he worked as a lecturer at the Non-commissioned Officer Vocational School in Balıkesir. Between 2014 and 2016, he worked as a personnel officer at the 8th Turkish Army Corps. Since 2017, he continues to work as a lecturer at the Mechanical Engineering Department at the National Defense University/Turkish Military Academy. He has studies and publications on machinability, ballistics, armor design, IEDs, and statistical test methods.

Emre Aytav – Lt. Col., Asst. Prof. Ph.D., graduated from the Technical Military High School in 1997. He studied at the Gazi Technical Educational University for the Turkish Land Forces (1997-2001). He graduated from the Gazi University, the Institute of Science and Technology, with a master's degree in 2005. He completed his second degree in 2013 at the Mechanical Engineering Department of the Balikesir University. He received his Ph.D. degree in Energy Technologies in 2018 at the Ege University. Between 2001 and 2015, he worked as a planning officer at the Non-commissioned Officer Vocational School in Balıkesir. From 2015-2017, he served as a planning officer at the Turkish Land Forces Operations Command. Since 2017, he continues to work as Assistant Professor at the Mechanical Engineering Department, the National Defense University/Turkish Military Academy. He has studies and publications on ballistics, terminal ballistic, energy technologies (renewable and sustainable energy, and biofuels).

Burak Çanakçi – Major, a lecturer, graduated from the Karadeniz Technical University in 2001. He received his MSc degree from the Omer Halis Demir University at the Mechanical Engineering Department in 2005. Between 2003 and 2016, he worked as the Mechanical Engineer in the Military Factories. Since 2017 he has worked as a lecturer at the Mechanical Engineering Department at the National Defense University/Turkish Military Academy. He has studies and publications on energy, wind turbine, thermodynamics, and statistical test methods.

Przegląd materiałów i struktur pochłaniających promieniowanie radarowe

STRESZCZENIE

Coraz większego znaczenia nabiera rozwój technologii mogących konkurować z produktami przemysłu obronnego używanymi przez inne kraje oraz, co istotniejsze, uniemożliwiać prawidłowe działanie tych produktów. Materiały pochłaniające promieniowanie (RAM – radiation-absorbent material) utrudniają wykrycie obiektu przez radar, absorbując część wiązki elektromagnetycznej wysłanej przez to urządzenie. Biorąc pod uwagę to, że radiolokacja stanowi jedną z najistotniejszych technologii stosowanych w przemyśle obronnym, produkcja materiałów zakłócających jej skuteczność ma kluczowe znaczenie dla wszystkich krajów świata. Pokrycie platformy bojowej materiałem pochłaniającym promieniowanie ogranicza skuteczną powierzchnię odbicia (SPO), od której zależna jest widoczność tej platformy na radarze. Niniejszy artykuł ma na celu przedstawienie zasad elektromagnetyzmu oraz rozwoju materiałów pochłaniających promieniowanie począwszy od lat sześćdziesiątych XX w. Fale elektromagnetyczne o częstotliwości 8-12 GHz określane są jako mikrofale i mają zastosowanie w urządzeniach radiolokacyjnych lotnisk. W artykule przedstawiono uaktualnione podstawy teorii elektromagnetycznej, zdefiniowano różnorodne materiały pochłaniające oraz przedstawiono niektóre typy i techniki.

SŁOWA KLUCZOWE

materiał pochłaniający promieniowanie,
pochłanianie promieniowania w ograniczonym zakresie widma,
stratny dielektryk, czynnik kształtu

How to cite this paper

Aytaç A, İpek H, Aztekin K, Aytav E, Çanakçı B. *A review of the radar absorber material and structures*. Scientific Journal of the Military University of Land Forces. 2020;52;4(198):931-46.

DOI: http://dx.doi.org/10.5604/01.3001.0014.6064