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CURRENT TRENDS IN THE RADAR ABSORBING MATERIALS

BY

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Abstract. The study of materials with properties of reducing or blocking electromagnetic radiation used in RADAR detection has gained momentum in recent years, especially after the discovery of graphene and metamaterials. The paper aims to present the main absorbing radar materials, the classic ones based on metal or carbon particles but also the recently discovered ones, based on complex mixtures of materials with good electrical, magnetic and thermal properties with dielectric materials.

Keywords: Radar absorbing materials (RAM), graphene, metamaterials, electrical conductivity.

1. Introduction

Over time, people have sought to develop methods and materials to "see" at distance, but also methods and materials to block "distance vision". One way to solve this problem was the RADAR (Radio Detecting and Ranging) technology that began to develop in the 1930s, exploring the potential of radio waves for detecting objects at distance; RADAR systems have been operating effectively since the Second World War (Vinoy and Jha, 1995; Wu *et al*., 2023).

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Later, these methods were used to control and monitor air and naval traffic or in meteorology. There are several ways to avoid radar detection, such as the use of specially designed materials and shapes that reduce the radar signature of an object (shapes with certain curves or inclined surfaces that reflect the radar beam in certain directions), metallization of windows (to avoid the phenomenon of reflection of radio waves from interior cavities) of jamming devices, the use of natural landforms or man-made structures to block the radar signature and more. In recent years, materials that give aircrafts "invisibility" - paints containing pigments with radar-absorbing properties have been studied and developed (RAM - Radar Absorbing Material) (Atay, 2017; Fu *et al*., 2022; Hu *et al*., 2023). These are special materials that have the property of absorbing radar signals, dissipating them into heat or other forms of energy and significantly reducing the reflectivity of aircrafts. This makes the aircraft less detectable by radar systems and therefore less "visible" to enemy radar detection systems. But the applications of materials with radar absorbing properties can be extended to other areas such as signature reduction radar of vehicles or buildings.

Radar absorbing materials are designed to significantly reduce the reflection of electromagnetic waves and to dissipate the incident electromagnetic energy as heat instead of sending it back into the environment. These materials are usually made up of a mixture of conductive and dielectric materials, which have properties of absorbing electromagnetic waves. Some radar absorbing materials contain also ferromagnetic particles to increase absorption of electromagnetic waves at higher frequencies. When an electromagnetic wave strikes the surface of an absorbing radar mixture, it penetrates the material and begins to interact with its components. When these components absorb electromagnetic energy, convert it into heat, through the process of converting electromagnetic energy into thermal energy. The absorption mechanism consists of converting the radar wave energy into heat or other forms of energy, through the processes of conduction, dielectric polarization or electromagnetic induction. This mechanism occurs when the radar wave interacts with the porous structure or conductive materials present in the composition of the RAM material. This heat is dissipated into the surrounding environment by two main mechanisms: convection and thermal radiation. Convection involves the transfer of heat through the movement of fluids such as air. Thermal radiation involves the transfer of energy in the form of electromagnetic waves, particularly in the form of infrared radiation. In general, the performance of radar absorbing materials depends on several factors, such as composition, thickness, shape, texture and frequency of the incident electromagnetic waves. Thus, radar absorbing materials are used in various applications, including the design of stealth aircraft, to reduce their radar signature (Huang *et al*., 2022; Saville *et al*., 2005; Stergiou *et al*., 2017).

To be effective, RAM materials must meet several conditions. First, they must have a porous structure or contain conductive materials that absorb radar energy. This means that the material must be able to convert the radar energy into heat or other forms of energy, instead of reflecting it back. These conductive materials can be made up of metallic or carbon particles, having a suitable thickness, generally between 1/4 and 1/8 of the radar wavelength, to ensure effective absorption of the radar waves (too small thickness will not be sufficient to absorb radar energy, while too much thickness will make the material too heavy and bulky). Also, RAMs must be able to absorb radar energy over a wide range of frequencies to work effectively against several types of radars. This means that the material must be able to absorb both shortwave and longwave radars. It is very important that the RAM withstand environmental conditions such as extreme temperatures, humidity and solar radiation. These conditions can affect the performance of the material over time, so they must be tested and verified to ensure proper operation. Last but not least, the material must have a low density, not affecting the weight and maneuverability of the radar system in which it is used. This is especially important in military applications, where targets must be mobile and easily maneuverable.

The main categories of radar absorbing materials are:

- Metallic materials, with good electrical and thermal conductivity,
- Dielectric materials with high losses (ceramic materials, polymers, ceramic-metal/polymer assemblies); (lossy dielectric materials)
- Magnetic materials with high losses (ferrites, ferrite-polymer assemblies or other magnetic composites);
- 2D or 3D metamaterials, with selective surfaces and periodic prints;
- Layered assemblies from the previously listed combinations.

All these materials must meet requirements from a mechanical point of view (stiffness, flexibility, ease of application, weight, ability to withstand vibrations/mechanical loads, etc.), chemically (chemically inert, stable to large temperature variations, resistance to corrosion, non-toxic, etc.), electro-magnetic (magnetic permeability, appreciable electromagnetic losses in the desired frequency ranges) and last but not least, easy to produce and affordable from a financial point of view.

Conductive RAM use materials such as carbon fiber or conductive metals to absorb radar waves. Magnetic RAM use materials with magnetic properties, such as iron microparticles or oxides, to absorb the waves. Among the most used RAM with conductive properties are assemblies containing metal microcrystals (iron, copper) or oxide nano-micro crystals (single or mixed) (Wu and Wei, 2012), carbon, nanomaterials, graphite or fullerene paints, polymers with conductive properties (Hu *et al.*, 2023; Stergiou *et al.*, 2017) or metamaterials with electromagnetic resonance structures, such as those with spiral technology (Wu *et al*., 2023).

They are applied on the surface of the aircraft and can be re-applied or replaced depending on the degree of wear or the evolution of radar technology.

When determining the radar absorbing properties of materials, the variation of reflection loss (dB) as a function of frequency (GHz) is usually followed. So, the radar-absorbing efficiency is defined as the ratio between the absorption power of the material and the incident power of the radar waves. To measure the radar absorbing efficiency of a material, a series of laboratory tests can be performed using a radar system: it generates a radar wave that is directed towards the material, and part of this wave is absorbed by the material, the difference between the incident power and the reflected or transmitted power can be used to determine the radar absorbing efficiency of the material.

There are several calculation methods to determine the effectiveness of radar absorbing materials, depending on how the experimental tests are performed and the characteristics of the materials studied. However, generally the formula for calculating the radar absorbing efficiency (R) of a material is (Eq. (1)):

$$R(dB) = 10lg\ [1 - (S_{11}/S_{12})] \tag{1}$$

where S_{11} is the reflection coefficient and S_{21} is the transmission coefficient for the studied material (Ibrahim *et al*., 2020; Wu *et al*., 2022). These coefficients can be determined experimentally, by means of a vector network analyser, which measures the amplitude and phase of the radar waves as a function of frequency.

It is also possible to calculate the efficiency of RAM materials depending on the impedance of the composite material and the impedance of the environment (air), described by the formula from Eq. (2) (Li *et al*., 2019):

$$R(dB) = 20lg\ (Z_{in}/Z_{air}) \tag{2}$$

where Z_{in} is the input impedance of the material (ie the impedance at the surface of the material) and Z_{air} is the impedance of the air (Ibrahim *et al*., 2020; Wu *et al*., 2022). This formula is based on the principle that an absorbing radar material must have an impedance as close as possible to the impedance of air, in order to minimize the reflection of radar waves.

The effectiveness and performance of RAM materials varies depending on the radar frequency and the physical characteristics of the substances used in the paint. Ideal absorbing materials should have some specific properties, such as low density, efficiency in thin layer, high absorption capacity and of course, high bandwidth - adaptability to absorb radiation with various frequencies (Shanenkov *et al*., 2017; Wu *et al*., 2022), and since they will have to work in quite harsh conditions, they must be resistant to temperature and corrosion (Huang *et al*., 2022; Ibrahim *et al*., 2020).

2. Materials containing metal nano/microcrystals and metal alloys

Among the first RAM materials was Fe ball paint, which contains microscopic spheres of Fe obtained by decomposing iron pentacarbonyl or with ferrite, suspended in an epoxy resin, which convert the energy of radar waves into heat (the heat is transferred to the aircraft and then dispersed). Usually, these metal spheres are coated with SiO_2 (as an insulator). In the manufacturing process of parts, when the epoxy paint containing Fe microspheres is not yet dry enough, a magnetic field is applied with a certain intensity and at well-calculated distance so as to obtain geometric patterns with iron/ferrite balls. The paint hardens by keeping the Fe spheres on fixed positions, uniformly dispersed, according to the models in Fig. 1.

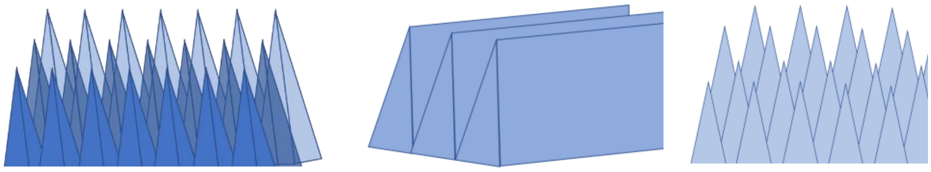
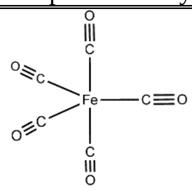


Fig. 1 – Periodic geometric structures designed to ensure radar invisibility.

Absorbent paints with ferrite arranged according to the models in Fig 1. in pyramidal or conical shapes are based on the principle of conical impedance (refers to the way in which the angle between the direction of the electromagnetic wave and the axis of the covering cone of an antenna determines the impedance of the air around it). Table 1 compares the physico-chemical characteristics of ferrites and iron pentacarbonyl-based radar absorption materials.

Table 1

Physico-chemical characteristics of ferrite and iron pentacarbonyl

Ferrite	Iron pentacarbonyl
- solid solution of carbon in Feα (approximately 0.002%C); - crystallized in isometric system with centered volume; - properties similar to pure Fe; - good mechanical properties, such as plasticity, ductility and toughness; - keeps its magnetic properties even at temperatures above 900K.	 $Fe(CO)_5$ - bipyramidal trigonal geometry; - yellow to bright orange liquid; - density 1.453 g·cm^{-3}; - volatile; - insoluble in water, soluble in organic solvents; - very toxic, flammable; - precursor in the synthesis of nanoparticles.

Ferrite doped with cobalt, zinc or nickel shows much better absorbing radar performance than iron oxide, (Huang *et al*., 2019; Zhao *et al*., 2016); thus, $CoFe_2O_4$ -C nanocomposites determine the maximum reflection loss value (maximum reflection loss value) of -49.6 dB at 9.2 GHz, due to the microporous structure and the strong synergistic effect given by the carbon matrix-magnetic nanoparticles assembly (Bhaskara Rao *et al*., 2022; Huang *et al*., 2019).

Apart from Fe powders/sheets or alloys, also known are those based on Au, Cu, Al or various metal alloys, due to their ability to absorb RADAR energy and the possibility of being incorporated into polymer matrices or can be used as coatings – metallization (in the form of microscopic particles or thin conductive films). These powders are prepared by grinding, spray technique or by hydrothermal / solvothermal methods, specific for each alloy and for the desired particle sizes, usually these being inserted in polymer matrices (Bhaskara Rao *et al*., 2022). Good results in the absorption of electromagnetic radiation were obtained for $Mn_{13-n}Co_n$ (n = 0 – 13) bimetal alloy clusters (Yin *et al*., 2019).

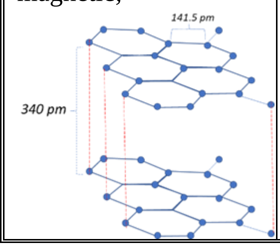
Aluminium is a highly reflective metal that can be used in RAMs by applying a thin layer of aluminium particles on the surface of an object.

This thin layer of aluminium can absorb radar energy and reduce the radar reflection. Good results were also obtained by controlling the distribution of Al particles in polyurethane composites, this assembly being a good absorber of infrared and electromagnetic radiation (it meets the requirements of stealth invisibility compatibility in two domains) (Shi *et al*., 2018). Likewise, Al/Fe_3O_4 composite material with core-shell structure, prepared by solvothermal synthesis, performed well as IR-absorbing and RADAR-absorbing material (Yuan *et al*., 2014).

3. Carbon-based radar-absorbing materials

Carbon is a versatile material with many classical applications. Carbon-based materials, for example amorphous carbon, carbon black or graphite, have been used for a long time as visible-absorbing materials (Hu *et al*., 2023). Recently discovered allotropic forms of carbon (graphene, fullerenes, nanotubes) have created the possibility to synthesize new materials, which absorb electromagnetic radiation of specific wavelength and have attractive mechanical properties. Some of the allotropic forms of C (natural or synthetic) are shown in table 2. The carbon in graphite, graphene, and carbon nanotubes is sp^2 hybridized, with a planar triangular geometry of the carbon atoms. This type of hybridization makes it possible to form a continuous band of carbon-carbon bonds. The sp^2 hybridization allows carbon to form strong covalent bonds between atoms, determining strong mechanical properties and bending resistance generating unique properties such as excellent thermal and electrical conductivity and high mechanical strength. Also, sp^2 hybridization in carbon nanotubes allows space to be created inside the tube, which makes it possible to use them in applications such as nanoelectronics and energy storage, and allows graphene to have a two-dimensional structure, which makes it possible to use it in electronic applications. The hybridization of carbon in fullerenes varies depending on the specific shape of the molecule. Some forms of fullerenes have sp^2 hybridized carbon, similar to graphene, while others have sp^3 hybridized carbon.

Table 2
Some allotropic forms of graphite with applications as materials with radar-absorbing properties.

Graphite	Graphene	Nano-carbon: fullerenes, nanotubes
- sp^2 hybridization - crystallized in a hexagonal system; - gray to black; - opaque; - optically anisotropic; - insoluble in acids; - boiling point 4200C; - when heated it becomes bipolar magnetic;  	- sp^2 hybridization; - the two-dimensional variant of graphite (isolated in 2004, by exfoliating graphite) (Novoselov *et al*., 2004); - optically transparent; - the best-known conductor of heat and electricity; - exceptional electronic mobility; - good mechanical properties, it is resistant to breaking but foldable, it is very light, it has high hardness; - multiple applications, in electronics, biomedical engineering, sensor industry, membrane production, etc.	- sp^2 hybridization; - they are dark-colored (black), opaque, low-hardness solids; - metamaterials from the structure of radar absorbing materials, composed of artificial periodic structure and dielectric substrate, (Huang *et al*., 2022); - nanostructured materials effective in absorbing radar radiation, due to design possibilities, small thicknesses and almost perfect absorption.

The sp^2 hybridization of carbon in fullerenes allows the formation of strong covalent bonds between atoms, which gives them unique properties such as high thermal and electrical conductivity. The sp^3 hybridization, on the other hand, allows less tight bonds to form between atoms, leading to different properties such as high thermal stability. Metal-carbon hybrid materials or carbon in various polymer matrices are usually used.

4. Composite materials with electromagnetic resonance structures

Materials with electromagnetic resonance structures are materials designed to have unusual optical properties due to the presence of regular geometric structures in the subwavelength scale of light and other electromagnetic radiation. These structures are designed to be of a certain configuration and size in order to cause electromagnetic resonance, that is, to amplify and direct electromagnetic waves in a certain way. These materials are usually called metamaterials and can be made from a variety of materials such as metals, dielectrics and even composites. They can be engineered to have unusual optical properties such as negative refractive index or complex refractive index, which makes them useful in a variety of applications such as photonics, optical communications, optical sensors, optical metamaterials, and more.

They contain special structures such as spirals or rings that resonate at the radar frequency and absorb radiation by resonance (Haitao *et al*., 2019; Lv *et al*., 2022; Tian *et al*., 2021). Among the oxide materials, zinc oxide, magnesium oxide, ZrO_2, or cupric oxide showed good results. Usually, these oxides are combined with other materials, such as carbon black or iron oxide, to enhance their performance (Ibrahim *et al*., 2020; Jun *et al*., 2009; Yang *et al*., 2021; Wang *et al*., 2021). Some of these composite materials with special structures, as well as their characteristics, are presented in Table 3.

Table 3

Various materials that have the property of absorbing radar radiation

Material	Manufacturing method	Characteristics	Reference
VO_2/ZnS core-shell	homogeneous precip. method	tunable emissivity properties, enhanced oxidation resistance	Ji *et al*., 2018
Cr_2O_3-Ag hybrid powders	electroless plating method air spraying	lower visible-near infrared reflectance, high radar wave transmission	Chai *et al*., 2021
Ag- Ti_3SiC_2 powders	electroless Ag plating	Ti_3SiC_2-30 wt% Ag powders, 2.0 mm thickness, the reflection loss is the minimum and the RL value is −24 dB at 10.9 GHz.	Liu *et al*., 2020
ZnO@SnO_2	hydrothermal method (SnO_2 nanowires epitaxially grow on the non-polarized plane of ZnO nanorods)	good IR-radar stealth performance	Zhang *et al*., 2017
$Sn_{0.84}Sm_{0.08}Sb_{0.08}O_2$ micro/nano fibers	electrospinning technique	multispectral compatible stealth properties	Xia *et al*., 2022
graphene - FeCo nanoparticles	solid-state technique, 700°C	reflection loss −71.63 dB at 10.8 GHz, - effective bandwidth 4.24 GHz, 2.68 mm thickness	Du *et al*., 2022

graphene oxide - Fe_3O_4	hydrothermal + freeze-drying processes	Max. abs. value: −31.3 dB - 15.3 GHz, 2.0 mm thickness	Wu *et al*., 2022
Au-decorated SWNT/PVDF	electrospinning technology	enhanced IR stealth performance	Fang and Fang, 2018
Al-doped ZnO nanoparticles	hydrothermal synthesis	IR emission and microwave loss properties	Wang *et al*., 2021
$K_{0.5}Na_{0.5}NbO_3$/ ZrO_2/Al_2O_3 heterojunction	3D plasma spraying technology.	radar-absorbing structure	Yang *et al*., 2021

Vanadium dioxide exhibits a metal-like conductivity at high temperatures and a dielectric-like conductivity at low temperatures. This property makes vanadium dioxide an excellent material for using it in RAMs, as it can effectively absorb radar energy and reduce the radar reflection (Chen *et al*., 2023; Duan *et al*., 2023).

These are just a few examples of the many materials that can be used in RAMs. It is important to note that while RAM can reduce the radar reflection from an object, it is not a guarantee of complete invisibility to radar. The effectiveness of RAM depends on the frequency of the radar system, the geometry and surface area of the object, and the type of RAM used.

5. Conclusions

RAM is a material used to reduce the amount of radar energy that is reflected back to the source. When a radar beam hits an object, it usually bounces back, creating a radar return. This radar return is what allows a radar system to detect the presence of an object. However, if the object is covered in RAM, the radar energy is absorbed by the material instead of being reflected back, which reduces the strength of the radar return and makes it more difficult for the radar system to detect the object.

In conclusion, RAM is a special material used to reduce the amount of radar energy that is reflected back to the source, making objects less visible to radar systems. By absorbing the energy from radar waves and converting it into heat, RAM can reduce the strength of the radar return and enhance the stealth capabilities of vehicles.

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TENDINȚE ACTUALE PRIVIND MATERIALELE CU PROPRIETĂȚI RADAR ABSORBANTE

(Rezumat)

Studiul materialelor cu proprietăți de a reduce sau chiar bloca radiația electromagnetică folosită în detecția RADAR a luat amploare în ultimii ani, mai ales după descoperirea grafenelor și a metamaterialelor. Lucrarea urmărește prezentarea principalelor materiale radar absorbante, a celor clasice pe bază de particule metalice sau carbon, dar și a celor descrise recent, pe bază de amestecuri complexe de materiale cu bune proprietăți electrice, magnetice și termice sau cu materiale dielectrice.