

## Synthesis of Nanocomposites Based on $\text{Fe}_3\text{O}_4$ and $\text{BaTiO}_3$ using Mechanical Alloying Method as Radar Absorbing Materials

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### ABSTRACT

This research focuses on the synthesis of a novel  $\text{Fe}_3\text{O}_4$ - $\text{BaTiO}_3$  nanocomposite, which serves as a highly effective radar-absorbing material. The synthesis of the  $\text{Fe}_3\text{O}_4$ - $\text{BaTiO}_3$  sample was accomplished through wet chemical methods, followed by high-energy mechanical alloying. This study assesses the structural and morphological characteristics of the nanocomposite utilizing X-Ray Diffraction (XRD), Particle Size Analyzer (PSA), and Scanning Electron Microscopy (SEM). The findings confirmed a successful reduction of the matrix dimensions to the nanometer scale, accompanied by a homogeneous integration of phases. These optimal heterogeneous nanostructures suggest that the  $\text{Fe}_3\text{O}_4$ - $\text{BaTiO}_3$  nanocomposite has considerable potential for the advancement of sophisticated stealth technology.

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## INTRODUCTION

In the current geopolitical context, which is increasingly complex and fraught with uncertainty, a nation's defense superiority is no longer solely assessed by its kinetic strength or the destructive capacity of its primary weapon systems. Instead, there has been a significant shift towards dominance in the realms of electronic warfare and information technology (Farooqui et al., 2023). One of the most critical aspects of modern air defense doctrine is the ability to operate undetected by adversary surveillance systems, a capability referred to as low observability or stealth technology (Feng et al., 2023). Radar, or Radio Detection and Ranging, serves as the foundation of Integrated Air Defense Systems (IADS) by emitting electromagnetic waves and analyzing reflected signals to identify the presence, position, speed, and identity of targets (Grobelny et al., 2023). Consequently, the ability to reduce the Radar Cross Section (RCS) of a combat platform—whether it be fighter aircraft, naval vessels, or Unmanned Aerial Vehicles (UAVs)—is of paramount strategic importance, significantly influencing survivability and mission success in contested environments (Calcara et al., 2023).

To mitigate the risk of detection, stealth technology incorporates Radar Absorbing Material (RAM), which operates by manipulating the fundamental principles of electromagnetic wave interaction with the material's surface (Wang et al., 2022). Radar Absorbing Material is specifically engineered to diminish the detectability of objects by radar systems, serving both military and civilian purposes (X. Zhang et al., 2022). One of the most significant applications of RAM is in stealth technology, where it reduces the radar cross-section (RCS) of vehicles such as aircraft, ships, and ground vehicles (Taufiq et al., 2020). By absorbing electromagnetic waves rather than reflecting them, RAM effectively renders these objects invisible to radar detection, which is crucial for military operations requiring stealth in hostile environments. Furthermore, RAM plays a vital role in safeguarding sensitive electronic equipment from electromagnetic interference, ensuring optimal performance in environments where multiple devices operate simultaneously (L. Zhang et al., 2021).

Among the various candidate materials for RAM, magnetite ( $\text{Fe}_3\text{O}_4$ ) has long been the subject of intensive research as a basis for radar-absorbing materials due to its superior ferromagnetic properties, high Curie temperature, low toxicity, and abundant natural availability, including in Indonesia's volcanic iron sands (Chatzimarkou & Stalikas, 2020). As a ferrimagnetic material with an inverse spinel crystal structure,  $\text{Fe}_3\text{O}_4$  exhibits excellent magnetic loss capabilities derived from natural resonance, eddy current loss, and domain wall resonance. However, the use of single  $\text{Fe}_3\text{O}_4$  nanoparticles as microwave absorbers encounters fundamental challenges, particularly severe impedance mismatch with free space (Song et al., 2020). At gigahertz (GHz) frequencies, pure  $\text{Fe}_3\text{O}_4$  tends to have a dielectric permittivity  $\epsilon$  that is significantly higher than its magnetic permeability ( $\mu$ ), resulting in most of the incoming electromagnetic wave energy being reflected directly off the material's surface before it can penetrate and be absorbed through magnetic loss mechanisms (Nikolaisen et al.,

2020). This phenomenon limits the absorption effectiveness and narrows the effective absorption bandwidth.

The development of multi-component nanocomposites that integrate magnetic materials such as  $\text{Fe}_3\text{O}_4$  with high dielectric materials like  $\text{BaTiO}_3$  represents a cutting-edge strategy for optimizing the electromagnetic wave absorption spectrum. The incorporation of  $\text{BaTiO}_3$  as a ferroelectric material with an exceptionally high dielectric constant significantly contributes to dielectric losses and the enhancement of dipole polarization within the composite structure (Huang et al., 2024a). The synergistic interaction between the magnetic phase ( $\text{Fe}_3\text{O}_4$ ) and the dielectric phase ( $\text{BaTiO}_3$ ) creates a complex heterogeneous interfacial network that triggers the Maxwell-Wagner-Sillars effect on a large scale (Ma et al., 2024). The double relaxation phenomenon resulting from this material combination allows for the simultaneous attenuation of radio frequency (RF) energy through complementary magnetic and dielectric losses (Chen et al., 2022). The accumulation of space charge at the nanometer-scale interfacial grain boundaries significantly enhances the conversion of microwave energy into thermal energy via polarization relaxation mechanisms (Yang et al., 2023).

## LITERATURE REVIEW

### *Radar Absorbing Material*

Radar Absorbing Material (RAM) is a functional material specifically engineered to effectively absorb radio frequency (RF) radiation and minimize wave reflection (Baek & Lee, 2021). The optimal performance of RAM is heavily reliant on the principle of impedance matching, where the material's impedance must be designed to closely approximate the free space impedance (approximately  $377 \Omega$ ) (Benderskiy et al., 2022). This condition allows electromagnetic waves to penetrate the material rather than reflect to the detector. To achieve this balance, RAM should not act as a perfect conductor or insulator; instead, it must possess lossy characteristics that effectively dissipate radar wave energy (Liu et al., 2022).

With the advancement of stealth technology, the latest RAM designs emphasize the creation of materials that are thin, lightweight, have broad absorption bands, and exhibit high durability using nanocomposites (Wu et al., 2022). These nanocomposites achieve superior performance by synergizing materials that contribute to magnetic loss (such as ferrites) and dielectric loss (such as carbon nanotubes or graphene oxide) within a particle size range of 1-100 nm (Okhapkin & Elizarov, 2022). The modulation of composition at the nanoscale not only facilitates precise impedance matching but also optimizes the attenuation of incoming waves through phenomena such as atomic absorption, hysteresis loss, and interfacial effects on nanofillers, making it a leading solution for next-generation microwave absorbing applications (V.G. et al., 2022).

### *Nanocomposite*

Nanocomposites are multifaceted materials containing fillers with dimensions in the nanometer range (1-100 nm), characterized by a significantly high surface-to-volume ratio. This property facilitates much more effective interfacial interactions compared to conventional composites (Al-husseiny &

Ebrahim, 2022). In the context of Radar Absorbing Material (RAM) applications, magnetic nanocomposites based on magnetite ( $\text{Fe}_3\text{O}_4$ ) play a crucial role in dissipating electromagnetic energy through magnetic loss mechanisms, including natural resonance, spin relaxation, and eddy current attenuation (Gandhi et al., 2024).

$\text{Fe}_3\text{O}_4$  is specifically selected as the primary absorbing phase due to its soft ferromagnetic properties, high saturation magnetization, and dynamic response to high-frequency radar waves (Abdo, 2021). The reduction of  $\text{Fe}_3\text{O}_4$  to the nanoscale also introduces superparamagnetic effects, which effectively broaden the resonance absorption bandwidth while minimizing static hysteresis losses (Y. Zhang et al., 2023).

To balance the magnetic components, Barium Titanate ( $\text{BaTiO}_3$ ) is integrated as a dielectric matrix phase to dampen the electric field components of radar waves (Guan et al., 2020). This attenuation mechanism relies on dielectric losses driven by intrinsic dipole polarization and interfacial polarization (Maxwell-Wagner-Sillars effect) (P. Zhang et al., 2021). The choice of  $\text{BaTiO}_3$  is based on its advantageous ferroelectric properties, which yield a very high dielectric constant, enabling it to create massive local charge accumulation centers when excited by high-frequency alternating electric fields (Huang et al., 2024b). The synergy between the magnetic losses of  $\text{Fe}_3\text{O}_4$  and the polarization capacity of  $\text{BaTiO}_3$  is pivotal in engineering nanocomposite materials to achieve optimal impedance matching conditions.

## METHODOLOGY

### *Materials and Tools*

Materials used in this research as follows,  $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$  from Supelco with 99.9% purity,  $\text{Fe}_2\text{SO}_4 \cdot 7\text{H}_2\text{O}$  from Sigma Aldrich with 99% purity,  $\text{BaCO}_3$  from Supelco with 99.9% purity,  $\text{TiO}_2$  from Sigma Aldrich with 99.9% purity.

Characterization of materials are using X-Ray Diffractometer (XRD) from RIGAKU using  $\text{Co-K}\alpha$  radiation ( $\lambda = 0.1789 \text{ nm}$ ), Particle Size Analyzer (PSA) from Nanoplus with nanometer precision, Scanning Electron Microscope ((SEM) from Hitachi SU-3500 with 100-20.000 times zoom scale

### *Synthesis*

The synthesis of magnetite nanoparticles ( $\text{Fe}_3\text{O}_4$ ) is conducted through a coprecipitation method, which involves mixing precursor solutions of  $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$  and  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$  at a molar ratio of  $\text{Fe}^{3+}:\text{Fe}^{2+}$  equal to 1.7:1. This mixture is heated to a temperature of  $80^\circ\text{C}$  while being stirred continuously (at 500-700 rpm) under a nitrogen gas flow to prevent oxidation. The precipitation process is initiated by the gradual addition of an  $\text{NH}_4\text{OH}$  solution until the suspension reaches a pH of 11-12, resulting in the formation of a dense black precipitate. Following a maturation (aging) period of 60 minutes at  $80^\circ\text{C}$ , the precipitate is separated using a neodymium permanent magnet, and then it is washed repeatedly with distilled water and ethanol until a neutral pH is achieved. The final product is obtained after the precipitate is dried in a vacuum oven at  $60^\circ\text{C}$  for 12 hours and then ground into a fine powder.

The synthesis of the dielectric material Barium Titanate ( $\text{BaTiO}_3$ ) is conducted through the solid-state reaction method, utilizing precursor powders of  $\text{BaCO}_3$  and  $\text{TiO}_2$  in a molar ratio of 1:1. The precursor mixture is subjected to intensive grinding for 2 hours using an agate mortar in a wet medium (ethanol or acetone) to enhance homogeneity, followed by drying in an oven at a temperature of  $100^\circ\text{C}$ . The resulting dry powder is then calcined in an alumina crucible using a high-temperature furnace with a heating rate of  $5^\circ\text{C}/\text{min}$  until it reaches a peak temperature of  $1100^\circ\text{C}$ , where it is maintained (dwelling) for 4 hours to ensure the formation of the tetragonal crystal phase of  $\text{BaTiO}_3$ . The calcined product is subsequently ground again and sieved through a mesh of 200-300 to obtain a fine powder with uniform particle size before it is utilized in the composite stage.

The integration of magnetic and dielectric phases for the synthesis of  $\text{Fe}_3\text{O}_4$ - $\text{BaTiO}_3$  nanocomposites is achieved through mechanical alloying utilizing High Energy Ball Milling (HEBM). Precursor powders of  $\text{Fe}_3\text{O}_4$  and  $\text{BaTiO}_3$  are weighed in a 1:1 weight ratio and subsequently placed into a stainless steel vial along with grinding balls of 5 mm and 10 mm in diameter, maintaining a ball-to-powder ratio (BPR) of 10:1. The wet milling process is conducted using a Planetary Ball Mill at a speed of 350 rpm for 1 hour, with the addition of toluene or ethanol as a Process Control Agent (PCA) to prevent excessive cold welding and minimize oxidation. This high-energy mechanical impact facilitates the reduction of particle size to the nanometer scale and the formation of a dense interface between the magnetic and dielectric phases. The resulting composite slurry is then dried in a vacuum oven to completely evaporate the PCA, yielding a fine powder of  $\text{Fe}_3\text{O}_4$ - $\text{BaTiO}_3$  nanocomposite that is ready for characterization.

### *Methods*

The characterization of the crystal structure and the identification of the constituent phases of the  $\text{Fe}_3\text{O}_4$ - $\text{BaTiO}_3$  nanocomposite were conducted using an X-Ray Diffractometer (XRD). This X-ray diffraction testing was performed with a  $\text{Co-K}\alpha$  radiation source to minimize the effects of secondary fluorescence, which typically occurs in iron (Fe)-rich material samples. Scanning was carried out over a specific range of  $2\theta$  angles with a constant scanning rate to produce a high-resolution diffractogram pattern. The obtained diffractogram data were subsequently analyzed and matched against the standard database of the Joint Committee on Powder Diffraction Standards (JCPDS) to validate the presence of the inverse spinel crystal phase of magnetite ( $\text{Fe}_3\text{O}_4$ ) and the perovskite phase of barium titanate ( $\text{BaTiO}_3$ ), as well as to confirm the absence of lattice shifts that could disrupt the structural order of the material post-synthesis.

The evaluation of the particle size distribution of the nanocomposite was measured using a Particle Size Analyzer (PSA) specifically calibrated for the nanometer measurement range. Prior to testing, a small amount of nanocomposite powder was dispersed in a solvent medium (such as distilled water or ethanol) and subjected to intensive sonication to break apart light agglomeration clumps, ensuring that the sample was homogeneously suspended. The measurements focused on utilizing the principles of dynamic

light scattering to detect the movement of primary particles in the liquid, which were then converted into a size distribution curve and the average particle diameter (D50) value. The data obtained from the PSA analysis play a crucial role in validating the success of the mechanical alloying method in reducing the dimensions of the  $\text{Fe}_3\text{O}_4\text{-BaTiO}_3$  material to a pure nanometer scale, which is a fundamental requirement for optimizing the interfacial polarization mechanism.

The topography and morphology of the surface of  $\text{Fe}_3\text{O}_4\text{-BaTiO}_3$  nanocomposite particles were meticulously examined using a Scanning Electron Microscope (SEM). Sample preparation involved placing the composite powder on conductive carbon tape, which was subsequently coated with a thin layer of conductive metal to prevent the accumulation of static charge (charging effect) during exposure to the electron beam. The morphological scanning of the specimens was conducted in stages, starting from an operational magnification of 100 times to monitor the macroscopic homogeneity of particle distribution, up to a magnification of 20,000 times to observe microscopic structural details with precision. The high-magnification microscopic images obtained provided visual confirmation of grain boundary density, surface topography of the particles, and the mechanical interlocking phenomenon occurring between the magnetic and dielectric phases.

## RESEARCH RESULT

### *Characterization of Nanoparticle*

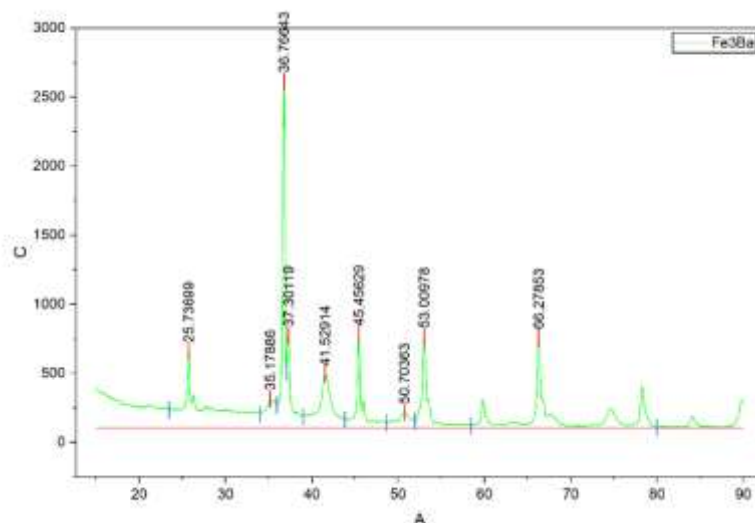


Figure 1. Diffraction pattern graph of  $\text{Fe}_3\text{O}_4\text{-BaTiO}_3$

The characterization stages of the structural nanocomposite  $\text{Fe}_3\text{O}_4\text{-BaTiO}_3$  commence with X-ray diffraction (XRD) testing over a  $2\theta$  angle range of  $10^\circ$  to  $90^\circ$ . The data analysis of the diffractogram is conducted through a systematic approach to accurately identify the crystalline phases. The analysis process begins with noise reduction and baseline correction using crystallographic software to distinguish the diffraction peaks from the background intensity. Subsequently, the extraction of the main diffraction peak positions is performed to obtain the  $2\theta$  angle values. The identification of the constituent phases is

executed through phase matching tests, comparing the experimental values against the Joint Committee on Powder Diffraction Standards (JCPDS) standard database. This analytical approach validates the existence of phases without necessitating excessive exposure of raw descriptive data within the text. A comprehensive visualization of the XRD scanning results is presented in Figure 1, while the results of the phase extraction are precisely summarized in Table 1.

Based on the visualization presented in Figure 1, the spectrum profile reveals a series of sharp and distinctly defined diffraction peaks, confirming the successful formation of a crystalline structure following synthesis. The diffractogram curve illustrates the coexistence of two sets of peaks that independently represent their constituent phases, with no detection of an amorphous phase (indicated by a flat curve) or secondary impurity peaks. This evidence substantiates that the mechanical alloying process effectively combined the magnetic and dielectric phases physically, without initiating secondary chemical reactions that could compromise the integrity of the atomic arrangement. To calculate the crystal size, use the following formula

$$D = \frac{K\lambda}{\beta \cos \theta} \dots \dots \dots (1)$$

Table 1. Crystal Structure and Crystal Size of Fe<sub>3</sub>O<sub>4</sub>-BaTiO<sub>3</sub>

| Phase                          | JCPDS   | 2θ    | Crystal Plane (hkl) | Crystal Structure | Crystal Size (nm) |
|--------------------------------|---------|-------|---------------------|-------------------|-------------------|
| Fe <sub>3</sub> O <sub>4</sub> | 19-0629 | 35,4° | (220)               | Cubic Spinel      | 6.52              |
|                                |         | 41,4° | (311)               |                   | 10.77             |
|                                |         | 50,8° | (400)               |                   | 10.16             |
| BaTiO <sub>3</sub>             | 05-0626 | 36,8° | (110)               | Tetragonal        | 36.64             |
|                                |         | 53,3° | (200)               |                   | 37.23             |

The data presented in Table 1 underscores that the high-intensity peaks are distributed in accordance with their crystallographic fingerprints. The characteristic peaks of the BaTiO<sub>3</sub> phase are validated at key angles that represent the perovskite structure, while the presence of the Fe<sub>3</sub>O<sub>4</sub> phase is predominantly confirmed at the (311) plane, which serves as a primary indicator of the formation of the inverse spinel magnetite structure. The integrity of these two nanometer-scale crystalline phases provides a fundamental foundation to facilitate the mechanisms of magnetic relaxation and interfacial polarization in mitigating electromagnetic waves.

The evaluation of the physical dimensions and particle size distribution of the Fe<sub>3</sub>O<sub>4</sub>-BaTiO<sub>3</sub> nanocomposite was conducted using a Particle Size Analyzer (PSA). To obtain data that accurately represents the material population, a quantitative statistical analysis was implemented through a grouped frequency distribution approach. The statistical calculation process commenced with the extraction of particle diameter values for each class interval, which were then multiplied by the percentage of their occurrence frequency. The results of these

multiplications were accumulated and divided by the total cumulative frequency (100%) to establish a theoretical estimate of the mean particle diameter.

Furthermore, the analysis also mapped the cumulative undersize parameters to determine the percentile cut-off points of the distribution, particularly the median value ( $D_{50}$ ), which represents the point at which 50% of the total particle population has dimensions below this size. The results of this descriptive statistical calculation are not presented in raw form within the narrative to avoid data redundancy; instead, they are comprehensively summarized in Table 2. Meanwhile, the visualization of the particle size distribution profile can be observed in Figure 2.

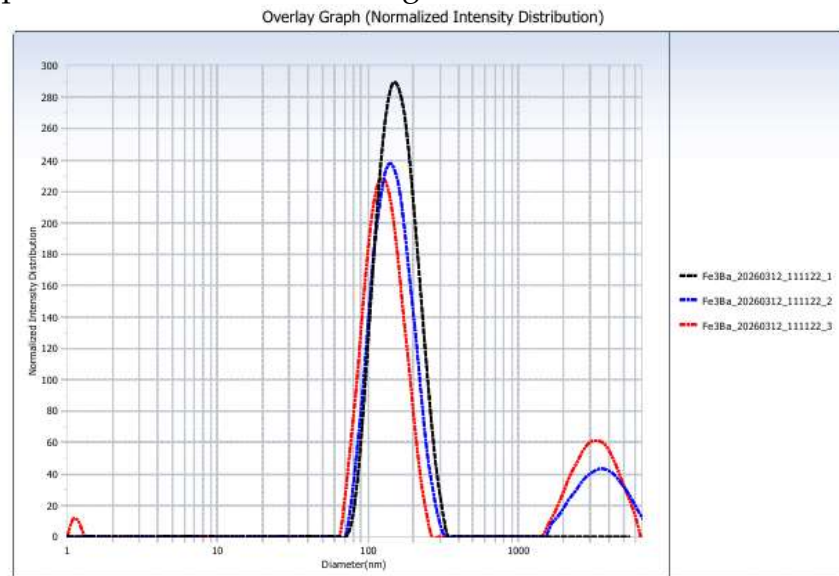


Figure 2. Particle Distribution Graph of  $\text{Fe}_3\text{O}_4\text{-BaTiO}_3$

The physical profile depicted in Figure 2 illustrates a distribution curve (asymmetric normal distribution) that extends from the nanometer scale to the lower boundary of sub-micron. This curve exemplifies the physical dynamics occurring post-synthesis; where the soft ferromagnetic phase induces some particles to undergo secondary agglomeration due to magnetic dipole attraction, yet the overall material distribution consistently maintains its nanostructural characteristics.

Table 2. Particle Distribution Size of  $\text{Fe}_3\text{O}_4\text{-BaTiO}_3$

| Distribution | Size (nm) |
|--------------|-----------|
| $D_{10}$     | 95.1      |
| $D_{50}$     | 144.6     |
| $D_{90}$     | 2251.9    |

According to the summary of the statistical test presented in Table 2, the convergence between the average value (mean) and the median point ( $D_{50}$ ) within the range of 144.6 nm demonstrates that the kinetic energy from the mechanical alloying process has successfully reached equilibrium. The reduction of the composite matrix predominantly remains below the macroscopic threshold. The success in maintaining the sizes of both primary and secondary

particles within this nanostructured regime is fundamentally significant, as the high surface area ratio will facilitate an increase in the density of heterogeneous grain boundaries, which directly serves to maximize the relaxation effects of polarization at the interface when the material interacts with radar waves.

The morphological characterization of the surface and topography of the  $\text{Fe}_3\text{O}_4\text{-BaTiO}_3$  nanocomposite was thoroughly evaluated using Scanning Electron Microscopy (SEM) instruments. The analysis commenced with specimen preparation, where the nanocomposite powder was dispersed onto double-sided conductive carbon tape and coated with a thin layer of metal to prevent electron charge accumulation (charging effect) that could distort the images. Morphological scanning was conducted in stages across varying magnification levels to observe the macroscopic distribution and the interactions of particles at the microscopic scale. To ensure that the analysis was not merely qualitative, image evaluation was supported by digital image processing software to systematically identify particle agglomeration patterns (cold welding), phase distribution, and geometrical arrangements.

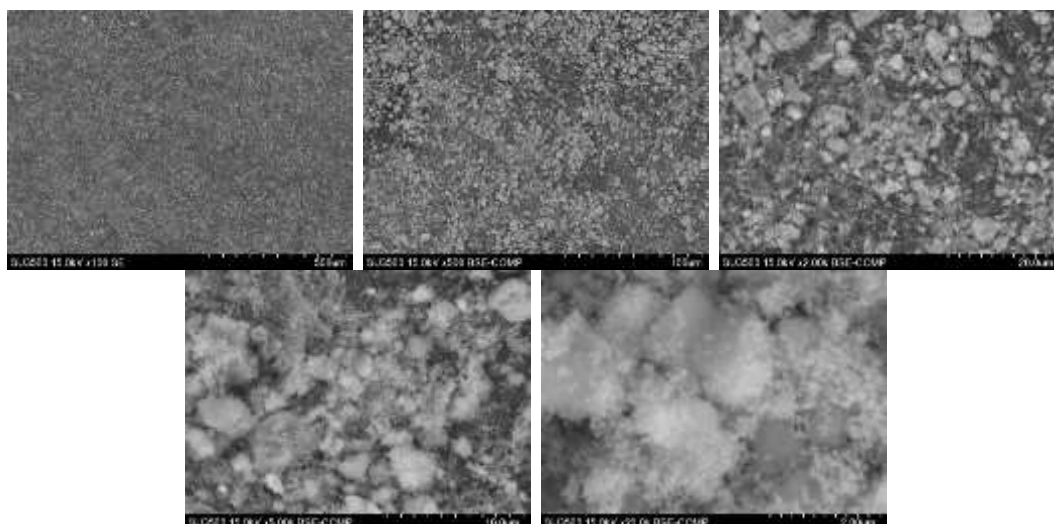


Figure 3. Topographic map of  $\text{Fe}_3\text{O}_4\text{-BaTiO}_3$  from a) 100x, b) 500x, c) 2.000x, d) 5.000x, and e) 20.000x

The results of the morphological scanning at different magnification levels are visualized in Figure 3. Rather than redundantly describing each image, the topographical parameters and physical findings from the SEM observations were extracted and summarized in a structured manner in Table 3.

Based on the visualization in Figure 3, it is evident that the material's morphology is dominated by solid aggregate structures at the macroscopic scale, with no isolated single nano crystals present. This visual appearance is a direct consequence of the high kinetic energy exposure during the mechanical alloying process. Details of the morphological parameters along with their physical implications are presented in Table 3.

Table 3. Summary of the Evaluation of Morphological Parameters of Fe<sub>3</sub>O<sub>4</sub>-BaTiO<sub>3</sub> Nanocomposites

| Morphological Parameters               | Results of SEM Image Analysis                                                                                                                                       | Physical and Mechanical Implications                                                                                                                                                         |
|----------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Particle Shape and Distribution</b> | Clumps formed in overlapping patterns with irregular surface geometries. No standalone primary particles were found.                                                | The high surface free energy causes the nanoscale particles to attract one another and agglomerate thermodynamically.                                                                        |
| <b>Interparticle Interactions</b>      | The particles physically bond together to form a dense, interlocking network.                                                                                       | Confirmation of plastic deformation and cold welding resulting from the impact energy of ball milling.                                                                                       |
| <b>Inter-Phase Dimensional Ratios</b>  | The dielectric-phase crystals (BaTiO <sub>3</sub> ) are larger in size and are surrounded by much finer magnetic-phase particles (Fe <sub>3</sub> O <sub>4</sub> ). | Differences in intrinsic mechanical strength: BaTiO <sub>3</sub> (tetragonal) is harder, while Fe <sub>3</sub> O <sub>4</sub> (soft ferrimagnetic) is more easily eroded into nanoparticles. |
| <b>Interface Density</b>               | The distribution of fine Fe <sub>3</sub> O <sub>4</sub> particles that are dense and adhere to the BaTiO <sub>3</sub> matrix surface.                               | Creating a massive network of heterogeneous interfacial contacts is crucial for triggering the interfacial polarization effect (Maxwell-Wagner).                                             |

The data summarized in Table 3 confirms that the differences in mechanical properties between Fe<sub>3</sub>O<sub>4</sub> and BaTiO<sub>3</sub> facilitate the formation of an ideal nanocomposite architecture. The erosion of Fe<sub>3</sub>O<sub>4</sub>, which subsequently envelops the BaTiO<sub>3</sub> matrix, demonstrates the successful integration of phases. This sub-micron interlocking morphology physically provides a highly dense interface contact area, which is an essential requirement for maximizing the attenuation of electric fields from radar waves through the interface polarization mechanism.

## DISCUSSION

The diffractogram obtained from the XRD characterization of the Fe<sub>3</sub>O<sub>4</sub>-BaTiO<sub>3</sub> nanocomposite as seen in figure 1 distinctly exhibits a series of sharp and well-defined diffraction peaks. This spectral profile confirms the successful formation of the crystalline structure of the material, which is homogeneously distributed and optimally maintained after the mechanical alloying process, without triggering secondary reactions or distorting into an amorphous phase as found in previous research (Chen et al., 2022). The preservation of the intact crystalline structure of both the magnetic and dielectric phases is a crucial physical foundation that ensures the stability of dynamic magnetic functionality and dielectric polarization capacity, thereby optimizing the dissipation of electromagnetic wave energy.

Based on the tabulated data on table 1, the presence of the soft ferromagnetic phase  $\text{Fe}_3\text{O}_4$  is strongly validated through characteristic peaks at diffraction angles ( $2\theta$ ) of  $35.4^\circ$ ,  $41.4^\circ$ , and  $50.8^\circ$ , which correspond to the Miller indices (hkl) (311), (400), and (511), respectively. Meanwhile, the dielectric phase  $\text{BaTiO}_3$  is detected with good resolution through the main peak at a  $2\theta$  angle of  $36.8^\circ$ , corresponding to the (110) orientation plane, and at  $53.3^\circ$  for the (200) plane. The matching of these specific values empirically confirms the coexistence of both phases, which successfully maintains the integrity of their crystalline order within the composite system.

The particle size distribution graph of the  $\text{Fe}_3\text{O}_4$ - $\text{BaTiO}_3$  nanocomposite on figure 2 illustrates a varied distribution curve ranging from the nano scale to sub-micron levels. Although the magnetic dipole attraction from the soft ferrimagnetic phase promotes secondary agglomeration among particles, the measured dimensions remain consistent within the categorization of the nanocomposite material system. The dominant particle distribution, which lies below the threshold of macroscopic agglomerates, demonstrates that the kinetic energy from the mechanical alloying process effectively reduces the composite matrix to a nanostructured scale, which is crucial for enhancing the relaxation effects of polarization at the interface when interacting with electromagnetic waves.

Based on the tabular data from the PSA testing on table 2, the determination of the average size of secondary particles was conducted using a statistical frequency distribution approach, yielding an estimated average diameter value of 144.6 nm. This quantification is validated by the cumulative undersize parameter in the table, which places the median distribution point (D50) precisely at the value of 144.6 nm. This figure indicates that half of the total population of  $\text{Fe}_3\text{O}_4$ - $\text{BaTiO}_3$  composite particles possesses physical dimensions below the threshold of 144.6 nm.

The morphological characterization of the surface using Scanning Electron Microscopy (SEM) on the  $\text{Fe}_3\text{O}_4$ - $\text{BaTiO}_3$  nanocomposite reveals a macroscopic aggregate topography characterized by the formation of interconnected and overlapping clumps. The absence of isolated pure nano crystals is a consequence of high kinetic energy exposure during the mechanical alloying process, which induces plastic deformation and cold welding among particles. This visual representation aligns closely with the results of the PSA characterization; the high surface free energy of nano-scale particles renders them thermodynamically unstable, leading to mutual attraction and interlocking to form a massive agglomeration network, thereby confirming the successful melting of the nanostructured fraction.

A more in-depth topographic analysis reveals a striking difference in physical dimensions between the constituent phases, where the dielectric crystal  $\text{BaTiO}_3$  is relatively larger than the magnetite crystal  $\text{Fe}_3\text{O}_4$ . This disparity arises from the high hardness and deformation resistance of the  $\text{BaTiO}_3$  phase, in contrast to the soft ferromagnetic phase  $\text{Fe}_3\text{O}_4$ , which is susceptible to mechanical forces and thus more easily reduced to nano dimensions. It is this difference in mechanical characteristics that physically supports the formation of the

nanocomposite compound, evidenced by the nano-sized  $\text{Fe}_3\text{O}_4$  particles adhering to and enveloping the surface of the  $\text{BaTiO}_3$  crystal. This unique morphological structure successfully creates a broad heterogeneous interfacial contact network, which triggers the interfacial polarization effect (Maxwell-Wagner) to maximize the attenuation of electromagnetic waves.

## **CONCLUSIONS AND RECOMMENDATIONS**

Based on the results of structural and morphological characterization, it can be concluded that the synthesis of the  $\text{Fe}_3\text{O}_4$ - $\text{BaTiO}_3$  nanocomposite via the mechanical alloying method has been successfully optimized. XRD testing confirms the coexistence of the crystalline phases of inverse spinel  $\text{Fe}_3\text{O}_4$  and perovskite  $\text{BaTiO}_3$ , maintaining the integrity of their atomic arrangement without triggering secondary chemical reactions or the formation of amorphous phases. The successful reduction of material dimensions is evidenced by PSA analysis, which shows a median particle size distribution ( $D_{50}$ ) of 144.6 nm, indicating a predominance of particles within the nanostructured regime. Furthermore, SEM observations reveal the topography of aggregates exhibiting interlocking phenomena and cold welding. The differences in mechanical resistance result in fine ferromagnetic  $\text{Fe}_3\text{O}_4$  particles densely enveloping the larger dielectric  $\text{BaTiO}_3$  matrix, thereby successfully creating a highly massive heterogeneous interfacial contact network.

The successful formation of this nanometer-scale heterogeneous interfacial architecture positions the  $\text{Fe}_3\text{O}_4$ - $\text{BaTiO}_3$  nanocomposite as a highly promising candidate for Radar Absorbing Material (RAM) applications in stealth technology. The tight contact network between the magnetic and dielectric phases plays a crucial role in inducing interfacial polarization effects (Maxwell-Wagner), which can maximize the attenuation of electromagnetic waves. As an application of this research, the formulation of the  $\text{Fe}_3\text{O}_4$ - $\text{BaTiO}_3$  composite is highly recommended for scaling up to manufacturing stages and integrating it as a base material for radar-absorbing coatings in tactical weapon systems. For future development, it is suggested to fabricate multilayer absorbers based on this material to test the efficiency of impedance matching and the widening of absorption bandwidth across a broader spectrum of operational radar frequencies.

## **ADVANCED RESEARCH**

This research is limited by the range of material compositions tested and the synthesis method restricted to mechanical alloying, which means that the resulting electromagnetic characteristics may not encompass all optimal variations across a broader frequency spectrum. Given the complexity of interfacial interactions in  $\text{Fe}_3\text{O}_4$ - $\text{BaTiO}_3$  nanocomposites, it is recommended that future studies explore a wider range of ball milling parameters, the use of additional dopants to enhance the dielectric constant, and the implementation of multilayer fabrication methods to achieve superior impedance matching performance and absorption bandwidth for more advanced air defense applications.

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