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Magnetic Behavior and Structural Properties of $Fe_{10}Al_{40}(ZnO)_{50}$ and $Fe_{10}Al_{50}(ZnO)_{40}$ Nanocomposites

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Abstract: Nanocomposite materials comprising $Fe_{10}Al_{40}(ZnO)_{50}$ and $Fe_{10}Al_{50}(ZnO)_{40}$ were synthesized using the powder metallurgy technique. The investigation of their structural, morphological, and magnetic properties at various synthesis stages was carried out utilizing advanced characterization methods, including Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), X-ray Diffraction (XRD), and Vibrating Sample Magnetometer (VSM). In the $Fe_{10}Al_{40}(ZnO)_{50}$ nanocomposite, the crystallite size was determined to be at its minimum, measuring 27.30 ± 5.82 nm, with the lattice strain (ε) reaching its maximum value of 0.155 ± 0.008%. Similarly, $Fe_{10}Al_{50}(ZnO)_{40}$ nanocomposite exhibited analogous trends in its structural and magnetic properties. Furthermore, the alteration in the mass ratio of aluminum and zinc oxide in the FeAlZnO nanocomposite influenced magnetic properties such as coercivity (Hc), magnetization saturation (Ms), magnetization remanence (Mr), and squareness (MR/MS). These findings indicate the potential of the FeAlZnO nanocomposite system as a high-frequency soft magnetic material.

Keyword: $Fe_{10}Al_{40}(ZnO)_{50}$ and $Fe_{10}Al_{50}(ZnO)_{40}$ Nanocomposites, Magnetic behavior, Structural properties, Morphology.

Introduction

In recent years, nanocomposite metal oxides have attracted a great deal of attention because of their amazing properties and great potential for a wide range of applications. Zinc oxide, one of the most popular semiconductor materials, comes in two basic crystalline forms: cubic zinc blende and hexagonal wurtzite. The zinc oxide displays antiferromagnetic behavior at room temperature; however, it can sometimes show ferromagnetic characteristics because of the existence of zinc or oxygen vacancies in the wurtzite crystal structure (Gur et al., 2022; Pushpalatha et al., 2022; Jiang et al., 2023; Chahal et al., 2023). Zinc oxide can be synthesized in a number of forms, including single crystals, sintered pellets, thick and thin films, as well as heterojunctions, enabling a large field of applications (Zonta et al., 2020; Benrezgua et al., 2022; Nguyen et al., 2020; Kumar et al., 2020; Guo et al., 2021). Incorporating iron and aluminum into zinc oxide gives hysteresis loops a sigmoidal shape, while retaining ferromagnetic properties at room temperature (Kuru et al., 2022; Ahmed et al., 2021). In contrast to other manufacturing procedures, mechanical alloying represents a very important and uncomplicated process. It has many advantages for growing nanostructured materials, enabling uniform distribution and homogeneity of particle components in accurate control (Suryanarayana, 2022; Sharath et al., 2024; Suryanarayana et al., 2022; Moravcik et al., 2020). Various types of characterization methods are employed in order to assess the structural, morphological and magnetic properties of milled powder, such as scanning electron microscopy (SEM), X-ray diffraction (XRD) and vibrating sample magnetometry (VSM).

In this research, the main aim is to investigate the impact of changing the chemical content of FeAl(ZnO) nanocomposites, in particularly by varying the quantities of Al and ZnO, on the structural and magnetic properties during mechanical alloying at room temperature. Additionally, this research aims to determine the optimal composition of the nanocomposite.

Materials and Experimental Procedure

Basic powders of Fe, Al and ZnO, having particle sizes of 70 µm, 60 µm and 60 µm and in purities of 99.3%, 99.15% and 99.22%, respectively, were milled in a high-energy PM400 planetary mill by the use of zirconium balls within argon atmosphere to obtain FeAl(ZnO) nanocomposites with changing concentrations. The weight ratio of powder to ball was around 1:10, and the milling speed was fixed at 280 rpm. The mixture of powders was milled in 20-minute cycles and then paused for 10 minutes.

The morphology and crystal structure of the samples were analyzed using a Gemini SEM 300 scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectroscopy (EDS) analyzer. The X-ray diffraction (XRD) analysis was carried out by means of a PANalytical XPERT-PRO diffractometer with Co-Kα radiation. The magnetic properties were determined using a vibrating sample magnetometer (VSM) under a maximum applied field of 15 kOe.

Results and Discussion

SEM Examination

The morphology and elemental distribution of FeAl(ZnO) nanocomposites at various compositions are depicted in Figure 1. Figure 1(a) displays $Fe_{10}Al_{40}(ZnO)_{50}$ nanocomposites, whereas Figure.1(b) indicates $Fe_{10}Al_{50}(ZnO)_{40}$ nanocomposites. Scanning electron microscope (SEM) images show a diversity of particle sizes, which could be due to the aggregation of smaller particles and the varying compositions of ZnO and Al within the nanocomposites.

The EDS spectra affirm the presence of Zn, O, Al and Fe, with each detected element at compositions matching their respective proportions in the various nanocomposite formulations. This coherence in the elemental composition of the samples demonstrates the perfect integration of ZnO and Al in the Fe matrix.

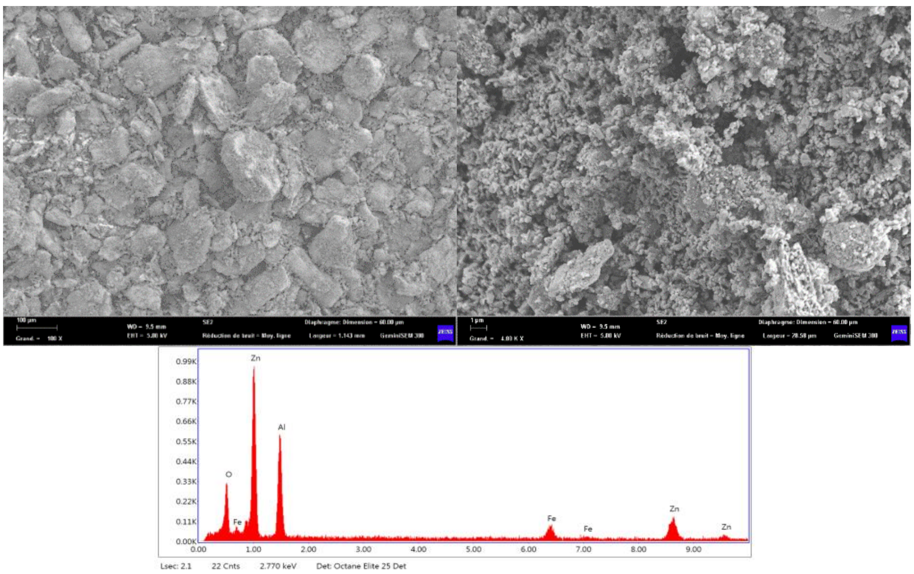

Figure 1.a. Morphology of $Fe_{10}Al_{40}(ZnO)_{50}$ nanocomposite

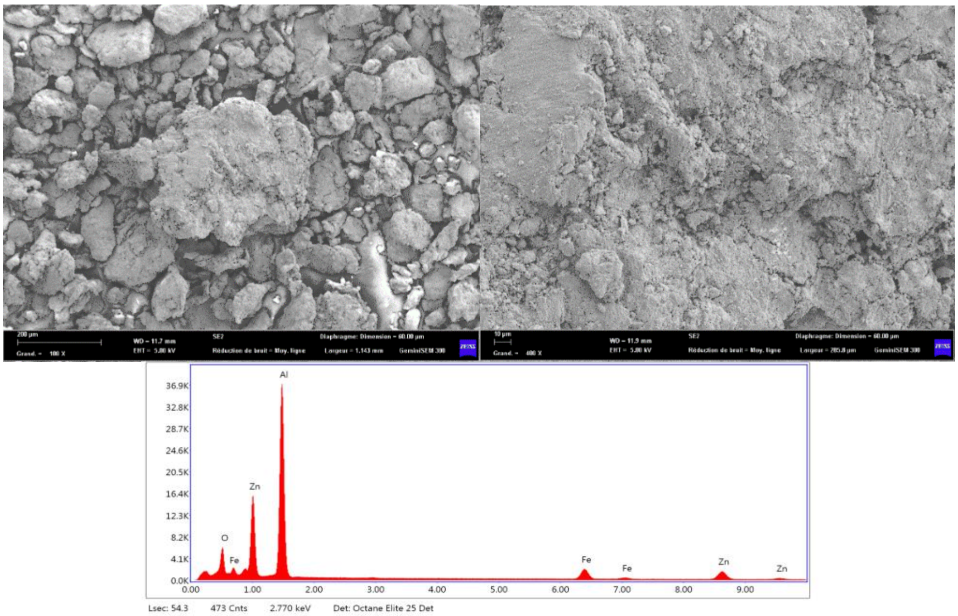

Figure 1.b. Morphology of $Fe_{10}Al_{50}(ZnO)_{40}$ nanocomposite

The variations in particle morphology observed in the SEM images indicate that the higher concentration of ZnO in the $Fe_{10}Al_{40}(ZnO)_{50}$ sample (Figure 1a) results in more pronounced aggregation, in comparison with the $Fe_{10}Al_{50}(ZnO)_{40}$ sample (Figure 1b). This difference could affect the total structural as well as the magnetic properties of the nanocomposites. Early reports (Rosowska et al., 2020; Tian et al., 2021) indicated that nanoparticle aggregation can have a significant effect on the physical characteristics of nanocomposites, potentially affecting their performance in different applications.

Structural Analysis

Figure. 2 displays X-ray diffraction patterns of FeAl(ZnO) nanocomposites at various compositions. All peaks match the hexagonal phases of the wurtzite structure of ZnO, the face-centered cubic crystal structure of aluminum, the iron-centered cubic phases and the new phases of the B2 structure of FeAl. The difference between both nanocomposites is the intensity and broadening of most peaks. The irregularity of the majority of peaks affirms the good crystallinity of the mechanically milled alloy (Peng et al., 2021). The X-ray diffraction (XRD) patterns of FeAl(ZnO) nanocomposites at various compositions are given in Figure 2. All the peaks observed match the hexagonal phases of the wurtzite structure of ZnO, the face-centered cubic (FCC) crystal structure of aluminum, the body-centered cubic (BCC) phases of iron and the new B2 phases of the FeAl alloy. The difference between the two nanocomposites lies in the intensity and broadening of most of the peaks.

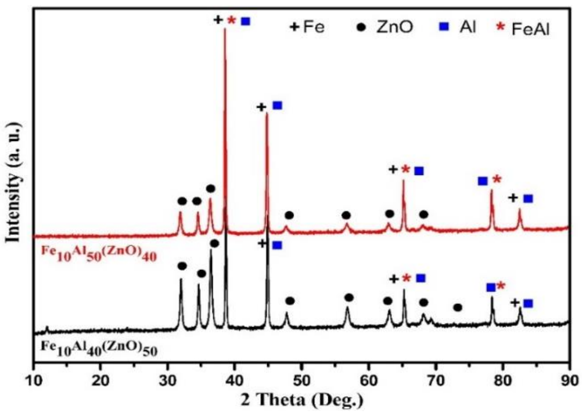

Figure 2. XRD patterns of FeAl(ZnO) nanocomposite with different concentration

The intensity variation and broadening of the peaks reveal differences in crystallite size and internal deformation within the nanocomposites. The pronounced sharpness of the majority of peaks confirms the good crystallinity of the mechanically milled alloy. In addition, the presence of broad peaks suggests a reduction in crystallite size and an increase in microstrain, which are typical results of high-energy ball milling (Peng et al., 2021). The strong crystallinity found in the XRD patterns is a testament to the efficiency of the mechanical alloying process in producing well-ordered nanocomposites. XRD analysis also shows that the composition of ZnO and Al strongly influences the structural characteristics of the nanocomposites, as shown by the different peak profiles in the diffraction patterns. Figure.3 presents the evolution of crystallite size and lattice strain in FeAl(ZnO) nanocomposites. These parameters were calculated using the Williamson-Hall method (Imtiaz et al., 2024), based on the maximum width at half maximum (FWHM) of the X-ray diffraction peaks.

The observed variation in crystallite size and increase in lattice strain could be attributed to severe plastic deformation induced during the mechanical alloying process. In addition, variation in chemical composition contributes to lattice distortions, resulting in high dislocation density. The severe plastic deformation splits the larger crystallites into smaller ones, increasing the number of grain boundaries and defects. In the meanwhile, the introduction of ZnO and Al into the Fe matrix causes lattice distortions due to differences in atom size and bonding characteristics, further increasing lattice strain. In summary, the combination of mechanical milling and compositional variations results in reduced crystallite sizes and increased lattice strain in the FeAl(ZnO) nanocomposites, as evidenced by the Williamson-Hall analysis.

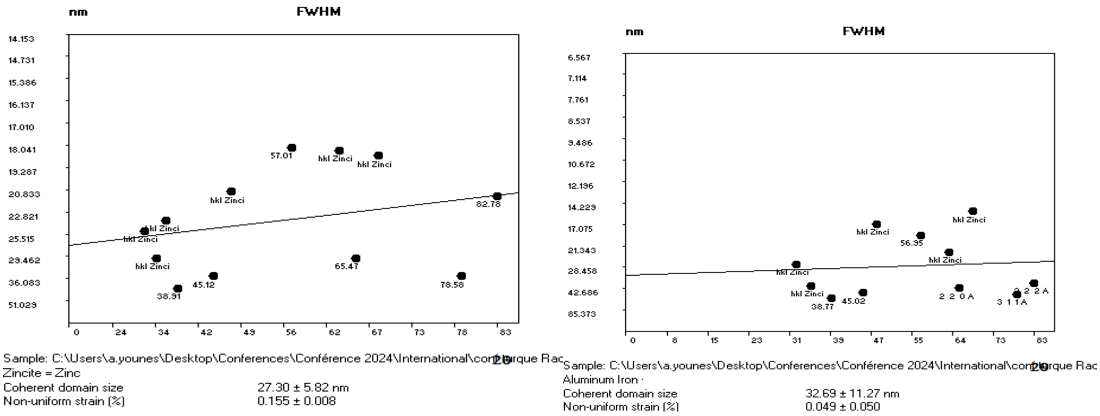

Figure 3. Crystallite size and lattice strain of FeAl(ZnO) nanocomposite with different concentration

Magnetic Characterization

In Figure 4, the hysteresis curves of $Fe_{10}Al_{40}(ZnO)_{50}$ and $Fe_{10}Al_{50}(ZnO)_{40}$ nanocomposites are plotted, at room temperature, by means of a vibrating sample magnetometer (VSM). The goal of this magnetic investigation is to assess the effect of different chemical compositions on the magnetic behavior of these nanocomposites.

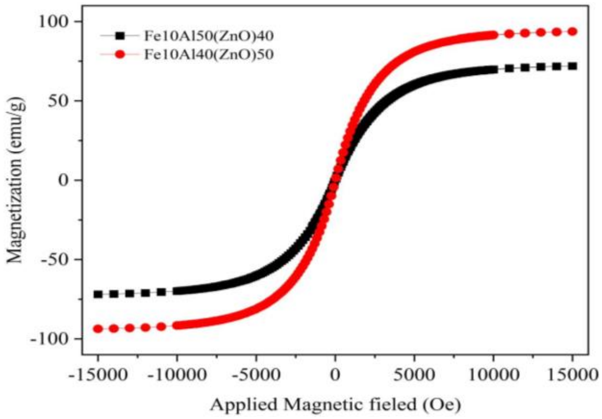

Figure 4. Hysreresis curve of $Fe_{10}Al_{40}(ZnO)_{50}$ and $Fe_{10}Al_{50}(ZnO)_{40}$ nanocomposites

Table 1 shows the magnetic parameters. Based on hysteresis curves, the magnetic properties of $Fe_{10}Al_{40}(ZnO)_{50}$ and $Fe_{10}Al_{50}(ZnO)_{40}$ nanocomposites differ significantly as a function of changes in their chemical composition. More specifically, variations in Al and ZnO compositions affect the saturation magnetization, coercivity and remanence of the nanocomposites. These differences can be attributed to the influence of Al and ZnO on the magnetic domain structure and interactions within the Fe matrix.

Table 1. The magnetic parameters of $Fe_{10}Al_{50}(ZnO)_{40}$ and $Fe_{10}Al_{40}(ZnO)_{50}$

$Fe_{10}Al_{50}(ZnO)_{40}$			$Fe_{10}Al_{40}(ZnO)_{50}$		
Hc (Oe)	Mr (emu/g)	Ms (emu/g)	Hc (Oe)	Mr (emu/g)	Ms (emu/g)
12,39	0,31	71,95	12,74	0,49	93,67

The results demonstrate that the $Fe_{10}Al_{40}(ZnO)_{50}$ nanocomposite exhibits different magnetic characteristics compared to the $Fe_{10}Al_{50}(ZnO)_{40}$ nanocomposite, highlighting the importance of chemical composition in tailoring the magnetic properties of FeAl(ZnO) nanocomposites. These findings are crucial for optimizing the magnetic performance of such materials for various applications (Khalid et al., 2019; Vijayakumar et al., 2020).

Conclusion

The study of FeAl(ZnO) nanocomposites has enabled us to gain a better understanding of the way in which variations in chemical composition can affect their structural and magnetic properties. X-ray diffraction analysis has shown that incorporating different concentrations of Al and ZnO leads to different changes in crystallite size and lattice strain, mainly due to significant plastic deformation and lattice distortions induced during mechanical alloying. Morphological analysis by SEM and EDS confirmed the successful incorporation of the elements Zn, O, Al and Fe into the nanocomposites, with variations in particle size attributed to aggregation phenomena and compositional differences. XRD diagrams also confirmed the formation of a well-crystallized nanocomposite with characteristic phases matching the wurtzite structure of ZnO, aluminum FCC, iron BCC and B2 FeAl phases. Magnetic characterization by hysteresis curve analysis confirmed that the magnetic properties of nanocomposites are extremely dependent on chemical composition. Variations in Al and ZnO compositions strongly influenced saturation magnetization, coercivity and remanence, indicating that magnetic behavior can be tailored by adjusting elemental proportions. In conclusion, the results highlight the critical role of chemical composition in determining the structural and magnetic properties of FeAl(ZnO) nanocomposites. This insight is essential for optimizing these materials for specific applications, which could enhance their performance in various technological fields.

Scientific Ethics Declaration

The authors declares that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Acknowledgements or Notes

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