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Development of a new magnetic aluminum matrix nanocomposite

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ABSTRACT

This article presents the results of a comparative investigation on microstructure, mechanical properties and magnetic characteristics of aluminum matrix nanocomposites reinforced with nickel ferrite nanoparticles. Magnetic nickel ferrite ($NiFe_2O_4$) nanoparticles with average size of 35 nm were synthesized via citrate-nitrate route and were used as the reinforcement phase in commercially pure aluminum matrix. Aluminum matrix samples with 0, 1, 2.5, 5 and 10 wt% ceramic reinforcement were fabricated using the powder metallurgy process. The sintered samples were then extruded at 400 °C to improve the density and homogeneity of the composite. Optical microscopy, SEM, FESEM, densitometry, XRD, DSC and VSM analyses were all used to evaluate the microstructure, porosity distribution, density, existing phases, possible reactions between the matrix and the reinforcements and magnetic properties of the samples. The results showed that the relative density of the composites decreased as the reinforcement weight percent was increased. The samples yield stress and ultimate tensile strength increased by increasing the weight percent of the reinforcement up to 5 wt%, however, they dropped at 10 wt% reinforcement content. The compressive yield stress, magnetization and coercivity of the composites were all observed to increase as the reinforcement content increased. However, the elongation of composite samples decreased considerably as the reinforcement content increased.

1. Introduction

Ferrites or ceramic magnetic materials are a very important group of magnetic materials. In regard to continuous development of magnetic materials, numerous research activities on ferrites during the last decades have led to innovative results such as theories, models and novel preparation technologies. Some typical applications of ferrites include motors, generators, transformers, sensors and telecommunication. The other materials cannot usually compete with ferrites due to their particular characteristics including high magnetic properties, low costs and convenient application. Superior magnetic properties of these materials basically originate from ferromagnetic elements including Fe, Co and Ni at room temperature [1].

Nickel ferrite ($FeNi_2O_4$) is a ceramic compound with a spinel structure and appropriate chemical and magnetic properties even at elevated temperatures which has many applications in electrical components, sensors, drug delivery and as catalysts [2–4].

Aluminum is a paramagnetic material which shows trivial magnetic properties in high magnetic fields. An aluminum matrix composite with magnetic properties offers several advantages in comparison with the traditional magnetic materials such as higher ductility, lower density and easier shaping process [5].

Adding magnetic ceramic reinforcements to the paramagnetic metallic alloys in order to fabricate metal matrix composites (MMCs) with unique magnetomechanical properties has not been well studied in the literature. For instance, Bayraktar et al. [6] added magnetic Fe_3O_4 particles to an aluminum matrix, however, they did not look into the magnetic properties of the synthesized composite.

MMCs are metallic alloys usually reinforced with ceramic materials to improve different properties [7–9]. During the past decades, metal matrix nanocomposites have been widely studied in the literature as advanced materials and have found several engineering applications because of their unique combination of metals and ceramics properties [10–14]. The most common matrices of MMCs are lightweight alloys, i.e. Al, Ti and Mg [8]. Nowadays, MMCs are quickly replacing monolithic alloys, and aluminum matrix composites (AMCs) are being mostly used because of their unique combination of properties such as light weight, high modulus, strength and hardness, controlled coefficient of thermal expansion, thermal stability, corrosion resistance, abrasion and wear resistance, good damping capability, improved operating

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temperature and low cost [15–17]. AMCs are used as high performance materials in various industries including aerospace, automotive, sport, marine and electronics [18–24].

Up to now, a variety of ceramic materials such as oxides, carbides, nitrides and borides have been used as the reinforcement in the aluminum matrix in order to improve various properties [25,26]. Nevertheless, SiC and Al_2O_3 are among the most commonly used reinforcements [27]. The ceramic reinforcements can decrease the density of the metal matrix composites [25], while the mechanical, electrical, chemical and physical properties of AMCs are enhanced by addition and dispersion of reinforcements in the matrix [27]. These properties depend on several factors including the manufacturing process, type and volume fraction of the constituents, morphology, distribution and size of reinforcing phase in the matrix, microstructure, defects especially pores and cracks, and effectiveness of the interfacial bonding between reinforcement and matrix [21,25,28]. Reactions may occur between the matrix and the reinforcement which results in the formation of undesired interfacial compounds [25]. On the other hand, reinforcing with thermodynamically stable materials that do not tend to undergo phase transformation or react with the matrix at high temperatures is necessary for a MMC to efficiently works at high temperatures [27].

It has been evidently shown that by reducing the reinforcement particle size from micron to nanometer, the number of barriers against dislocation motion in the unit volume of the matrix increases which improves the mechanical properties. On the other hand, a very fine particle size for the reinforcement may lead to excessive agglomeration and poor distribution of particles in the matrix [5,7,29].

Composite fabrication methods are divided into four major categories including solid, liquid, semisolid and vapor state routes [30,31]. Powder metallurgy route is a solid state processing method which involves blending, ball milling, compaction and sintering of carefully selected powders. Some advantages of the powder metallurgy route include homogeneity of the constituents, appropriate mechanical properties, near net shape dimensions, reasonable costs and high automation and industrialization potential [32].

Accordingly, adding nickel ferrite nanoparticles to an aluminum matrix is expected to produce a lightweight metal matrix composite with proper magnetic properties to be used in several industries such as automotive, aeronautical and sensitive measurement instruments. In this study, attempts were made to synthesize aluminum matrix composites containing different amounts of magnetic nickel ferrite nanoparticles and evaluate their microstructure, mechanical properties and magnetic characteristics.

2. Experimental procedures

2.1. Synthesis of nanoparticle

Nickel ferrite nanoparticle were synthesized by citrate-nitrate route as proposed by Allafchian et al. [33]. Iron nitrate ($Fe(NO_3)_3{\cdot}9H_2O$) and nickel nitrate ($Ni(NO_3)_2{\cdot}6H_2O$) were used in a stoichiometric ratio of 2:1 as the starting materials. First, 0.02 mol of citric acid was diluted with a small quantity of distilled water. The precursors were then stir dissolved in the aqueous solution at 30 °C to achieve a clear solution. pH value of the solution was adjusted to about 9 by adding 0.1 mol L^{-1} of ammonium hydroxide. The gelation reaction was completed within 2 h. Finally, the resultant gel was dried at 100 °C for 24 h and then calcined at 600 °C for 2 h in an argon atmosphere. A scanning electron micrograph of the synthesized nickel ferrite nanoparticles is shown in Fig. 1. As shown in this figure, the average size of nickel ferrite nanoparticles measures approximately 35 nm.

2.2. Preparation of nanocomposites

Commercially pure aluminum powder with particle size < 63 µm (Khorasan powder metallurgy Co., Mashhad, Iran) (Fig. 2) and the abovementioned synthesized nickel ferrite nanoparticles were used as the raw materials. Mixtures of aluminum powder and 0, 1, 2.5, 5 and 10 wt% nickel ferrite nanoparticles were blended in a planetary ball mill using ball to powder weight ratio of 10 and revolution of 250 rpm for 2 h under argon atmosphere.

Each resultant powder mixture was compacted at ambient temperature in a die (D = 20 mm) under uniaxial pressure of 200 MPa to prepare cylindrical samples. The samples were subsequently sintered in a tubular furnace at 600 °C for 1 h under argon atmosphere. As can be seen in Fig. 3, the sintered samples were hot extruded at 400 °C to a rod of 7 mm diameter with an extrusion ratio of 8. The preparation conditions for samples were chosen based on Issa et al. [13].

2.3. Characterization

Differential scanning calorimetry (DSC) of the samples was performed using a DSC machine (model TA-1A, Pishtaz engineering Co. instruments, Iran) under nitrogen atmosphere at a heating rate of 10 °C/min. Different phases presented in the samples were identified by a Philips X-ray diffractometer (Cu K_α, $\lambda = 1.54$ Å).

The composites microstructure was observed by optical microscope and scanning electron microscope (SEM Philips XL30 FEG). Relative density of the bulk samples were obtained according to Archimedes principle. Tensile and compression tests were carried out according to ASTM E8M-04 [34] and ASTM E9–89a [35] standards, respectively. In addition, Brinell hardness (BHN) of the samples was measured according to ASTM-E10 standard [36]. Magnetic properties of the composite samples were characterized using vibrating sample magnetometer (VSM, Danesh Pazhouhan Kavir Kashan Co. (MDKFD), Kashan, Iran) at room temperature.

3. Results and discussion

3.1. Stability of the reinforcement phase

A prerequisite of any particle to be used as reinforcement in a metal matrix is no occurrence of undesirable reaction with the matrix during processing or service. A thermal analysis was conducted to evaluate the stability of $NiFe_2O_4$ nanoparticles in the aluminum matrix. DSC curve of Al-10%$NiFe_2O_4$ nanocomposite is shown in Fig. 4. This sample was selected for thermal analysis because it had the highest nickel ferrite content, which facilitates the peaks detection. The DSC curve reveals an endothermic peak around 660 °C and an exothermic peak around 800 °C. The endothermic peak corresponds to aluminum melting temperature and the exothermic one is presumed to be due to the reaction of nickel ferrite with aluminum.

According to Fig. 4, no reaction is expected to occur between aluminum and nickel ferrite below 800 °C. This ensures that nickel ferrite nanoparticle is thermodynamically stable as the reinforcement for the aluminum matrix, particularly in a solid state processing, and under service even at high temperatures.

3.2. Phase identification

Fig. 5 shows the XRD pattern of pure nickel ferrite nanoparticle. It is a well-known fact that the peak broadening occurs in nanoparticulate materials due to very fine crystallite size. Furthermore, since no peak for any other phase is detected, the pattern confirms that a single phase material has been synthesized by the citrate-nitrate route.

XRD pattern of the product of the thermal analysis of Al-10% $NiFe_2O_4$ nanocomposite is shown in Fig. 6. The exothermic peak in Fig. 4 revealed a reaction between nickel ferrite and aluminum; however this was not detectable in the XRD pattern of the product. This is believed to be due to the low content of the reaction product compared to the matrix and also very close position of the most intensive XRD peak of alumina and that of aluminum peaks.