Abstract

Ferromagnetic materials are a group of materials that can display strong magnetism in the direction of the externally applied magnetic field. Exhibiting strong magnetic properties of these materials can be attributed to the presence of domains inside those materials. Each domain is a small region where all of the atomic dipoles are coupled together in a preferential direction. Therefore, ferromagnetic materials have a large, positive susceptibility and many of them (cobalt, nickel, gadolinium, iron, etc.) can be converted into permanent magnets or 'hard ferromagnetic material' (hard magnets) using an external magnetic field. On the other hand, the soft ferromagnetic materials (soft iron, steel) can be easily magnetized and demagnetized and are used in electromagnets, communication equipment, and transformers. The hard magnetic materials that show hard magnetic properties (coercivity, energy product and remanence) are also used in transducers, magnetic tapes, digital computers, magnetic nanofluids etc. The present research deals with the development of some permanent magnetic materials including some applications of ferromagnetic materials in hard magnetic devices.

The demand for permanent magnets is rapidly growing in our daily life as they serve as essential components in a wide range of applications such as electric motors, loudspeakers, computers, compact disc players, microwave ovens, toys, and refrigerators. Permanent magnetic materials play a critical role in devices for power conversion for the electrical grid, transmission of electric power and energy storage. There is a growing demand for Nd-Fe-B and Sm-Co permanent magnets with high coercivity and large energy product. These magnets have been the focus of research for almost the past 30 years. While magnets are increasingly dependent upon rare-earths, there has been an effort to replace them with their alternative rare-earth-free compositions because of the high cost involvement during extraction of the rare-earth materials from their ore. In this research, the rare-earth-free Zr-Co system was chosen primarily because (1) the high-anisotropy Zr-Co alloy structures forms in a rather broad composition region as compared to the equilibrium bulk phase diagrams and (2) the Zr-Co system exhibits a high Curie temperature (T_c) of above 750 K and a high energy product $(BH)_{max}$ (about 4.3-12.6 MGOe), which are comparable to those of alnico and RE containing materials.

For the development of rare-earth-free permanent magnets with better performance to cost ratio, V and B dopings were employed to enhance the hard magnetic properties of Zr-Co-V-B alloys. The effect of V and B microalloying additions on the magnetic properties, phase stability and microstructure of the metastable Co_5Zr phase have been investigated with experimental measurements together with first principles based on the DFT (Density Functional Theory) calculations. This study also investigates the effects of annealing at different temperatures on the intrinsic and extrinsic magnetic properties of $Co_{82}Zr_{12}V_{6-x}B_x$ melt-spun ribbons. Rapidly solidified $Co_{82}Zr_{12}V_{6-x}B_x$ (x= 1, 2, 3) alloy ribbons were produced by the vacuum melt-spinning technique. The amorphous alloy ribbons were annealed in a vacuum furnace at a series of temperatures of 600 °C, 650 °C, 700 °C and 750 °C, each for 30 minutes. Annealed sample $Co_{82}Zr_{12}V_5B_1$ showed the maximum coercivity value of 3.58 kOe that can be attributed to the formation of a high volume fraction of hard magnetic phase (Co_5Zr) and evenly distributed finer grains throughout the matrix.

Another attempt has been made on the investigation of the role of Boron (B) and Silicon (Si) additions in $Co_{79}Zr_{13}V_5B_1Si_2$, $Co_{79}Zr_{13}V_5B_{1.25}Si_{1.75}$, $Co_{79}Zr_{13}V_5B_{1.5}Si_{1.5}$, and $Co_{79}Zr_{13}V_5B_2Si_1$ ribbons in as-spun as well as in annealed conditions (annealed at various temperatures). The $Co_{82-(x+y)}Zr_{13}V_5B_xSi_y$ (x= 1, 1.25, 1.5, 2); (y= 2, 1.75, 1.5, 1) ribbons mainly contain rhombohedral Co_5Zr phase and a small amount of Zr_2Co_{11}, fcc-Co and cubic Zr_6Co_{23} phase. The addition of small amounts of Boron (B**)** reduces the grain size of the magnetic phases, and thus increases coercivity. Silicon (Si**)** addition enhances the anisotropy field of the hard phase which increases the coercivity but slightly decreases the magnetization. It has been observed that with an increase in annealing temperature beyond 650 ºC, the amount of the soft magnetic phases ($Co_{23}Zr_6$ and fcc-Co) have increased, while the amount of hard magnetic Co_5Zr phase is decreased. It has also been observed that the replacement of B with Si leads to an increase in the coercivity value of 6.14 kOe. High coercivity values were observed in all the ribbons annealed at 600 ºC and 650 ºC. Microstructural analysis has shown fine grains with an average grain size of 100-150 nm in $Co_{79}Zr_{13}V_5B_1Si_2$ and $Co_{79}Zr_{13}V_5B_2Si_1$ ribbons annealed at 650 °C.

This research also includes some investigations based on the other ferromagnetic materials' applications. The research has been carried out for the study of heat transport

phenomena with the application of synthesized Sm-Co hard magnetic nanofluids. In this work, research has been focused on the study of enhancement in thermal conductivity of silicone oil on increasing wt. % of hard magnetic Sm-Co nanoparticles (NPs) in the presence of varying external magnetic fields. Sm-Co-based NPs were synthesized using the low temperature 'Pechini-type sol-gel' process. Structural studies of the nanoparticles were performed by XRD, FESEM, TEM and FTIR. Mixed phases were noticed through XRD, FESEM and TEM. Sm-Co nanoparticles were then uniformly dispersed in silicone oil to design Sm-Co magnetic nanofluid (MNF) systems of various weight percent concentrations. The maximum thermal conductivity enhancement ~ 373% is attained at 15 wt. % concentration and at 0.5T magnetic flux density for Sm-Co magnetic nanofluids.

Also, the research has proposed a simulation-based optimized design of the MRI magnet system by replacing shielded coils with a ferromagnetic shell to generate a spatially homogeneous, constant magnetic field gradient and thus, to create suitable conditions for MRI to reduce electricity consumption. The addition of a ferromagnetic shell resulted in a 19% reduction in the current requirement. Also, the ferromagnetic shell allowed the MRI system to get reduced by 5% in length. The difference in ampere turn is similarly noticeable, with a difference of 12%.

Keywords: Co-Zr-V-B alloy; Coercivity; Remanence; Magnetization; Hard phase; Soft phase; Permanent magnet; Doping element; Microstructure; Sol-gel process; Magnetic-nanofluids; Silicone oil; Magnetic field induced thermal conductivity; Current density; Ferromagnetic shell; Field homogeneity; Optimization.