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Magnetic and structural anisotropic properties of magnetostrictive Fe-Ga flake particles and their epoxy-bonded composites

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ABSTRACT

Flake shaped particles of grain-oriented $Fe_{80}Ga_{20}$ and $Fe_{73}Ga_{27}$ alloys were prepared using a high-energy wet ball-milling process. The surface of flakes produced were predominantly parallel to the (1 0 0) crystallographic plane in flakes. These flakes possess two in-plane ⟨1 0 0⟩ easy axes of magnetization, which enhances magnetostrictive performance and sensitivity for use in composite materials. The deformation mechanism leading to formation of (1 0 0) grain-oriented flakes is associated with small angel crystal reorientations along slip lines similar to what occurs during rolling. Data are presented on the in-plane magnetic properties of these flakes, which were characterized using field-dependent magnetization measurements. The epoxy-bonded composites with the particle alignment exhibited high magnetostriction values of ~103 ppm.

Building on the discovery of single crystal Fe-Ga alloys known as Galfenol, which have good magnetostriction of ~400 ppm along the ⟨1 0 0⟩ orientation [1], interest in using Fe-Ga particles for production of composite magnetostrictive actuators and sensors has grown in the past decade [2–4]. Magnetostrictive composites offer useful bandwidth at high frequencies by surrounding magnetostrictive particles, which have a high electrical resistivity, in a non-conducting binder [5]. The particles employed in previous works on magnetostrictive Fe-Ga composites were conventional powders that were spherical in shape and comprised of (1 1 0)-oriented grains. This led to magnetostrictive performance less than 64 ppm in the epoxy-bonded composites [2,3]. In contrast, recent work investigated the use of Fe-Ga flakes in composite transducers and demonstrated promising performance for ultrasonic guided wave sensing for use in a structural health monitoring system [6]. In these works, the flake-based composite transducers showed good directional sensitivity and much better sensing performance than composites fabricated using granular or spherical particles. In this letter, we report magnetic and structural properties of Fe-Ga flakes and composites, including microstructure and texture analysis.

Flake-type particles were produced from chill cast ingots of $Fe_{80}Ga_{20}$ and $Fe_{73}Ga_{27}$ alloy by high-energy ball milling with the following procedure. The ingots were initially crushed, then pulverized into coarse pieces with dimensions of several millimeters. Equal weights of stainless steel balls and pulverized alloy pieces were placed in a steel jar, the jar was filled with isopropyl alcohol and then placed in a SPEX 8000 Mixer/Mill for ~8 h as required for all alloy pieces to be fully transformed into flakes during milling. This was sufficient time for the pulverized alloy pieces to be reduced down to the micron sizes of less than 250 and 200 μm for $Fe_{80}Ga_{20}$ and $Fe_{73}Ga_{27}$ alloys, respectively. Wet ball milling, using isopropyl alcohol, was employed to avoid shattering alloy pieces into irregular powders, which occurs during dry milling. To examine the relationship between properties and flake size, a set of 5 sieves with grids opening of 45, 100, 150, 200 and 250 μm were used to separate the milled particles into five different size distributions. The size and shape of particles were examined using a scanning electron microscopy (SEM). Microstructure and texture analysis were conducted using X-ray diffraction (XRD), transmission electron microscopy (TEM) and detailed EBSD scans. The magnetic properties were measured by a vibrating sample magnetometer (VSM) equipped with a physical property measurement system (PPMS: Model 6000, Quantum Design, Inc.).

Flake-shaped particles of soft metals such as aluminum (Al) are usually prepared by ball-milling of spherical powders transformed to two-dimensional particles that provided good shape comparability with one-dimensional materials such as carbon nanotubes. In contrast, Fe-Ga flakes were fabricated from alloyed bulk pieces

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using wet milling techniques, not synthesized from different two elements. Fig. 1(a) shows XRD data of as-milled flakes sorted by size. Based on sieve grid opening sizes, the average particle sizes in the different groups were determined to be 23, 73, 125, 175 and 225 μm. The size distribution and microstrain for the both alloys are summarized in Table 1, indicating the $Fe_{73}Ga_{27}$ alloy is more brittle than $Fe_{80}Ga_{20}$ alloy. The efficacy of this milling protocol for producing flakes is indicative of high microstrain introduced as a consequence of the ball impacts on the flake surface. After hot pressing, the strain level subsequently decreased to 0.0035, which is one third ($\varepsilon = 0.0105$) of the as-milled flakes with the average size of 73 μm.

The microstructure of both alloy flake particles mainly consists of the disordered A2 phase with a BCC α-iron structure. Here, it is obvious that no reflections from $L1_2$ FCC intermetallic (Fe_3Ga) phase were observed in either alloy.

Interestingly, we found that as the particle size increases, the flake surface tends toward being parallel to the (2 0 0) plane rather than the closed-packed (1 1 0) plane. The formation of a (2 0 0) surface plane has been shown to arise as a result of cleavage crack propagation that occurs on cube-face {1 0 0} crystal planes in BCC metals [7]. This occurs even though the {1 0 0} plane is not a slip plane in the BCC structure. The reason for this appears to be that dislocation pile-ups occur on {1 0 0} planes and result in the formation of wedge cleavage cracks that act as sources for crack nucleation and propagation along the (2 0 0) surface plane. It is also possible that ⟨1 1 1⟩ slip directions play a significant role as a dislocation-gliding path, disrupting the interaction that milling impacts might otherwise promote between low energy {1 1 0} slip planes. The dislocation reaction along mutually oriented ⟨0 0 1⟩ crystal axes can be modeled as $(a/2)[1\ 1\ -1]_{(101)} + (a/2)[-1\ -1\ -1]_{(-101)} = a[0\ 0\ -1]_{(001)}$, where a is a lattice parameter [8].

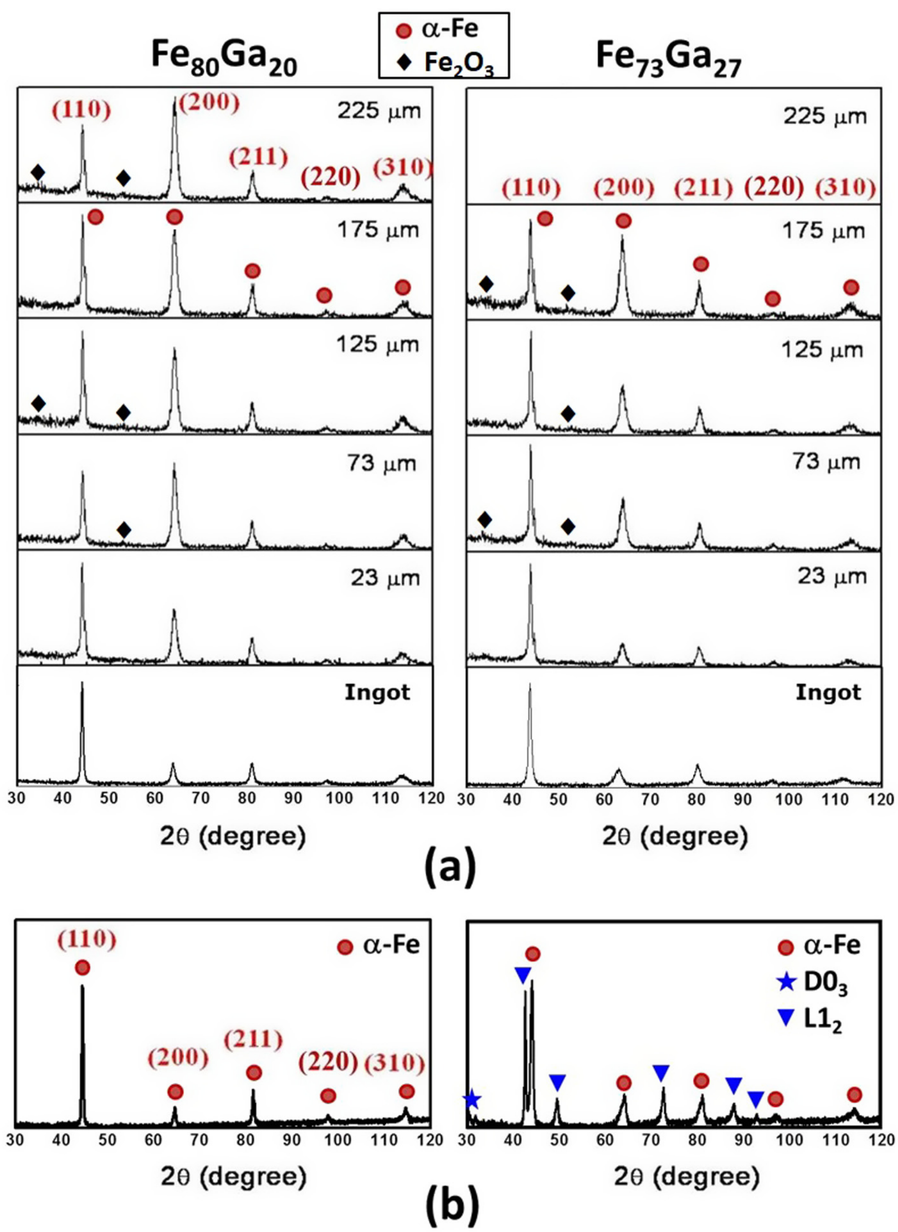

Fig. 1. X-ray diffraction patterns of (a) ingot materials and flake particles of $Fe_{80}Ga_{20}$ and $Fe_{73}Ga_{27}$ alloys with varying average particle sizes and (b) hot-pressed disc samples at 850 °C for 8 h for the both alloys with the average particle size of 73 μm.