Large Magnetostriction in Epoxy-Bonded Terfenol-D Continuous-Fiber Composite With [112] Crystallographic Orientation

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A Terfenol-D continuous-fiber composite with a preferred [112] crystallographic orientation was fabricated by embedding 50-vol% [112]-oriented Terfenol-D continuous fibers of 45 mm long and 1 mm wide in an epoxy matrix, and its magnetic and magnetostrictive properties were evaluated as a function of magnetic field. A [112]-oriented short-fiber composite with reduced Terfenol-D fiber lengths of 4 mm and a randomly oriented particulate composite with irregularly shaped Terfenol-D particles of 10–300 μm size, both with 50-vol% Terfenol-D, were also prepared and characterized for comparison with the continuous-fiber composite and monolithic Terfenol-D. The continuous-fiber composite demonstrated the largest magnetostrictive response with the highest saturation magnetostriction (λ_S) of 1265 ppm. This λ_S not only is 23% and 92% larger than the short-fiber and particulate composites, respectively, but also exceeds the monolithic Terfenol-D by 14%. The higher λ_S compared to the monolithic Terfenol-D, short-fiber composite, and particulate composite mainly originates from the residual compressive stresses developed in the continuous fibers during epoxy cure, a higher fiber aspect ratio for greater stress transfer from the fibers to the matrix, and texturing of the fibers along the highly magnetostrictive [112] crystallographic axis, respectively.

***Index Terms*—[112] crystallographic orientation, domain-wall motion, fiber composites, magnetostriction, particulate composites, Terfenol-D.**

I. Introduction

EPOXY-BONDED Terfenol-D particulate composites based on irregularly shaped, randomly oriented Terfenol-D particles (10–300 μm size) possess the distinct advantages of increased operational bandwidths, reduced mechanical brittleness, added property-tailorable capability, and reduced material costs as compared with monolithic Terfenol-D [1]–[4]. While these composites have been used in device applications [5], [6], their magnetostrictive properties, in particular the saturation magnetostriction (λ_S), are limited to ~60% of their monolithic material, significantly impeding their commercial viability [7], [8].

We have reported that improved magnetostrictive properties can be achieved by making composites with [112]-oriented Terfenol-D short fibers [9]–[11]. It is recalled that irregularly shaped Terfenol-D particles possess a random crystal orientation; accordingly, the best possible behavior for the resulting particulate composites is polycrystalline behavior with magnetostrictive properties substantially lower than the [112]-textured behavior exhibited by monolithic Terfenol-D. By using [112]-oriented Terfenol-D short fibers (4 mm long, 1 mm wide), the highly magnetostrictive [112] easy axis of monolithic Terfenol-D has been successfully created in composites, leading to an enhanced λ_S reaching 80%–90% of the monolithic Terfenol-D [9]–[11].

Recently, we have further increased the fiber length and prepared [112]-oriented Terfenol-D continuous (or long) fibers of 45 mm long and 1 mm wide (Fig. 1). Based on the continuous fibers, we have also fabricated [112]-oriented continuous-fiber composites exhibiting even larger magnetostrictive response with λ_S in excess of 10%, 20%, and 90% in comparison with the monolithic Terfenol-D, short-fiber composites, and particulate composites, respectively. In this paper, the processes for making the composites are disclosed, and the quasi-static magnetic and magnetostrictive properties of a 50-vol% continuous-fiber composite are reported, together with a monolithic Terfenol-D, a 50-vol% short-fiber composite, and a 50-vol% particulate composite. Composites with this volume percent can generally provide valid performance data for benchmarking purposes [4], [8].

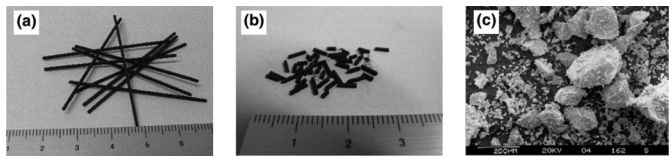

Fig. 1. Micrographs showing (a) [112]-oriented Terfenol-D continuous fibers, (b) [112]-oriented Terfenol-D short fibers, and (c) randomly oriented Terfenol-D particles.

II. Composite Fabrication

The [112]-oriented continuous fibers with a square cross section were cut along the long axis of a [112]-textured monolithic Terfenol-D plate ($Tb_{0.30}$ $Dy_{0.70}$ $Fe_{1.92}$) (Baotou Rare Earth Research Institute, Inner Mongolia, China) using an electrical discharge machining (EDM). The length and width of the fibers were 45 and 1 mm, respectively [Fig. 1(a)]. Using the same technique, the [112]-oriented short fibers were also prepared to have lengths of 4 mm and widths of 1 mm [Fig. 1(b)]. The irregularly shaped, randomly oriented particles were obtained by ball-milling a similar Terfenol-D rod in an inert gas environment. They had randomly distributed sizes of 10–300 μm

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in at least one dimension [Fig. 1(c)]. Araldite LY564/HY2954 epoxy was used as the matrix material for the continuous-fiber, short-fiber, and particulate composites. To fabricate the continuous- and short-fiber composites, predetermined quantities of Terfenol-D fibers were aligned along the longitudinal direction of a mold under a static magnetic field of ∼150 kA/m, and the composites were then preformed using a vacuum resin transfer molding process [8], [9]. For the particulate composite, predetermined quantities of Terfenol-D particles and epoxy were homogenously mixed and degassed in a mold before magnetic alignment of particles was performed [3], [4]. This magnetic alignment of particles essentially produces particulate chains in the composite (or a pseudo-1–3 composite in general) [4]. After cure at room temperature, all the composites were demolded and postcured at 70 °C for 8 h. The volume percents of the composites were confirmed to be 50 ± 1 based on the Archimedes's principle and rule-of-mixtures formulation.

III. Quasi-Static Measurements

The quasi-static magnetic and magnetostrictive properties of the fabricated composites and monolithic Terfenol-D were measured in the longitudinal direction at room temperature and with zero stress bias using an in-house automated measurement system [4]. Measurements of the magnetization-field $(M$–$H)$ curves and magnetostriction-field $(\lambda$–$H)$ curves were conducted by energizing an electromagnet to provide a cyclic magnetic field (H) with the maximum amplitude of 450 kA/m at 0.2 Hz and then measuring the corresponding magnetic flux density (B) and magnetostriction (λ) using a search coil wrapped around the samples and a strain gauge attached to the samples, respectively. The magnetization (M) associated with the captured B and H was calculated using

$$M = \frac{B}{\mu_o} - H \tag{1}$$

where $\mu_o = 4\pi \times 10^{-7}$ H/m is the permeability of free space.

IV. Results and Discussion

The magnetostriction-field $(\lambda$–$H)$ curves for the continuous-fiber composite, monolithic Terfenol-D, short-fiber composite, and particulate composite are shown in Fig. 2. All reported values are the second cycle results that discard the effects of an unknown initial magnetic domain state on λ. It is clear that while all samples readily reach their saturation magnetostrictions (λ_S) at 450 kA/m, the continuous-fiber composite demonstrates the largest magnetostrictive response for almost the whole H range and saturates with the highest λ_S of 1265 ppm. Importantly, this significantly large λ_S is 14%, 23%, and 92% larger than the monolithic Terfenol-D (1115 ppm), short-fiber composite (1030 ppm), and particulate composite (660 ppm), respectively. The higher λ_S when compared to the monolithic Terfenol-D is mainly attributed to the residual compressive stresses developed in the continuous fibers during the thermal cure of the epoxy matrix [4], [11]. These built-in residual compressive stresses effectively create a preferred non-180° domain state in the composite similar to the case of applying an external prestress to assert an initial

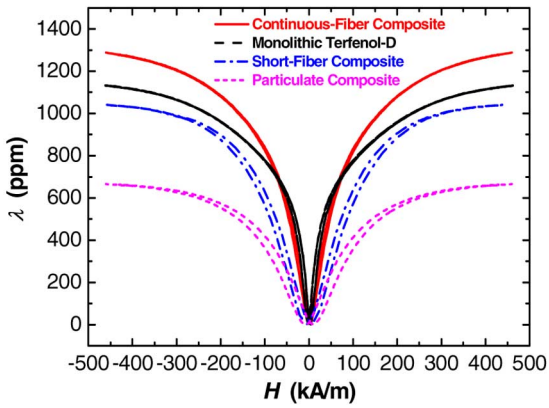

Fig. 2. λ–H curves for the continuous-fiber composite, monolithic Terfenol-D, short-fiber composite, and particulate composite. (Color version available online at http://ieeexplore.ieee.org.)

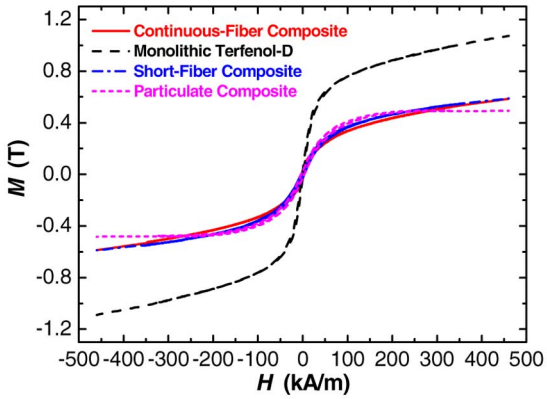

Fig. 3. M–H curves for the continuous-fiber composite, monolithic Terfenol-D, short-fiber composite, and particulate composite. (Color version available online at http://ieeexplore.ieee.org.)

non-180° domain state in monolithic Terfenol-D. By contrast, the monolithic material has comparatively little initial non-180° domains since the only internal stresses come from the ones generated by crystal defects and material processing [1], [2]. The generally larger λ–H response, together with the higher λ_S, in comparison with both the short-fiber and particulate composites is principally due to a longer fiber length (a higher aspect ratio), which not only allows greater stress transfer from the continuous fibers to the epoxy matrix (Fig. 1) but also mitigates more effectively the effect of demagnetization fields arisen from the reduced fiber aspect ratio [8]. The overall enhancement as seen in the fiber composites rather than in the particulate composite is a result of the [112]-texturing in the fiber composites even though both the increased effect of λ (and λ_S) and decreased effect of demagnetization fields in the higher aspect ratio fibers are still active [8]. It is noted that the [112]-texturing, which has been shown to effectively increase deformation contributions from non-180° domain-wall motion in the short-fiber composites [9]–[11], should also have a significant effect on the continuous-fiber composite.

The magnetization–field $(M$–$H)$ curves for all the samples are illustrated in Fig. 3. The results agree with those in Fig. 2 that all samples basically attain their saturation magnetizations (M_S) at 450 kA/m. The three composite samples possess quite

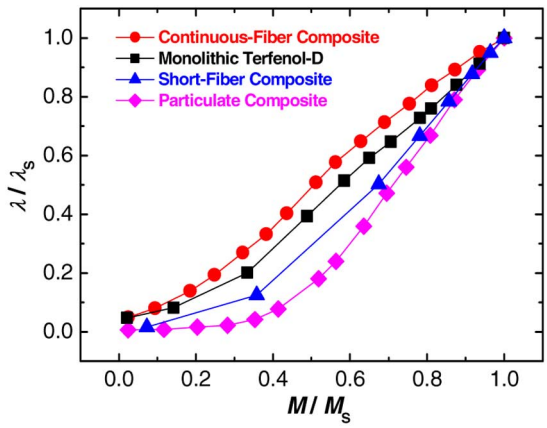

Fig. 4. $\lambda/\lambda S - M/M_S$ plots for the continuous-fiber composite, monolithic Terfenol-D, short-fiber composite, and particulate composite. (Color version available online at http://ieeexplore.ieee.org.)

similar magnetic hysteresis loops, but these loops are quite different from the monolithic Terfenol-D. This indicates that the M–H behavior of the samples is rather independent of the fabrication process; it mainly depends on the intrinsic magnetic properties of the materials and also the Terfenol-D volume percent instead. It is obvious that M_S of the composites are half-reduced from the monolithic Terfenol-D due to the one-half reduction in the Terfenol-D volume percent in the composites in general. Nevertheless, the M–H curves for the continuous- and short-fiber composites display relatively gentle slopes compared to the particulate composite for small H of < 100 kA/m and then show a faster increase with increasing H with larger M_S. The initial observation is characterized by the initial increased M contribution from the available and relatively easy 180° domain-wall motion in the particulate composite. The later observation is caused partially by the later increased M contribution from the non-180° domain process associated with the effect of fiber texturing along a [112] crystallographic axis and by the decreased effect of demagnetization fields in the larger aspect-ratio fibers.

Fig. 4 plots the magnetostriction ratio (λ/λ_S) versus the magnetization ratio (M/M_S) over a full magnetization for all samples so as to further understand their magnetization processes. The values of λ_S and M_S are extracted from Figs. 2 and 3 at $H = 450$ kA/m, respectively. It is clear that the magnetization process of the continuous-fiber composite is mainly governed by the motion of the non-180° domain walls, while that of the particulate composite is controlled predominately by the motion of the 180° domain walls for $M/M_S < 0.2$. This can be understood when considering that the 180° domain-wall motion results in changes in M without accompanying λ, whilst the non-180° domain-wall motion produces changes λ rather than changes in M. As this plot is independent of demagnetization fields, the enhanced magnetization process as seen in the continuous-fiber composite is directly attributed to its increased residual compressive stresses, increased aspect ratio, and the [112] texturing as compared with the monolithic Terfenol-D, short-fiber composite, and particulate composite, respectively.

V. Conclusion

A comparative study of the quasi-static magnetic and magnetostrictive properties of [112]-oriented continuous-fiber composite, [112]-oriented short-fiber composite, randomly oriented particulate composite, and monolithic Terfenol-D has been carried out in this study. The continuous-fiber composite has the strongest magnetostrictive response with the largest λ_S of 1270 ppm. This value is 14%, 23%, and 92% larger than the monolithic Terfenol-D, short-fiber composite, and particulate composite, respectively, and can be explained predominately by the residual compressive stresses developed in the fibers during epoxy cure, a higher aspect ratio for greater stress transfer from the fibers to the matrix, and texturing of the fibers along the highly magnetostrictive [112] crystallographic axis, respectively. It is believed that the significant property improvement in the continuous-fiber composite will broaden the practical use of magnetostrictive composites.

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