PROGRESS IN THE DEVELOPMENT OF TEXTURED DYSPROSIUM FOR UNDULATOR APPLICATIONS*

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Abstract

RadiaBeam Technologies is in the process of developing bulk textured dysprosium as a potential replacement for CoFe steel as undulator poles. For cryogenic undulators that can be cooled below the ferromagnetic transition of dysprosium, textured dysprosium offers potential increase in the peak field of the undulator. Here we report on the progress of the project, including magnetization curves for the material.

INTRODUCTION

The operation of cryogenic permanent magnet undulators (CPMUs) at temperatures below the Curie transition of rare-earth metals offers the opportunity to develop new pole materials that take advantage of the existing cryogenic conditions to potentially produce higher peak field undulators. To this end, RadiaBeam Technologies has been investigating the use of dysprosium and gadolinium to replace the cobalt-iron (CoFe) typically used in high field hybrid undulators. CoFe is the pole material of choice for high field undulators because of its large saturation magnetization (2.35 T), very large initial permeability ($\mu_i \sim 10^4$) and small non-linear knee region which is the transition between the two regions. In single crystal form, dysprosium demonstrates much higher magnetic moment (>3 T [1]) at low applied field and cryogenic temperatures than CoFe [2]. However, single crystals of these materials are difficult and expensive to produce at the dimensions and scale required for undulator fabrication and polycrystalline versions of the materials are not useful for undulator applications because of low initial permeability.

A compromise between the single crystal and polycrystalline forms can be reached through a processing technique that generates so-called texture in the material. This technique takes advantage of a favorable energy difference between crystallographic orientations during a rolling and annealing cycle [3]. Briefly, the polycrystalline material is rolled out and then annealed near the melting point. For dysprosium, which has an *hcp* structure, grains within the foil that are oriented with the hardest axis within the plane of the foil are taken over by grains that have the hardest axis pointed normal to the plane of the foil in a process known as secondary re-crystallization. This process dramatically increases the permeability within the plane of the foil [1]. The foils can then be annealed together in stacks to produce a macroscopic piece for further machining.

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MATERIAL DEVELOPMENT

We have previously reported the results of magnetic measurement of the textured dysprosium [2]. Those results showed that the textured dysprosium, made up of 100 μm thick foils, used in the initial 2-period prototype would not produce an improvement in peak field over CoFe poles. In that publication we suggested several changes that might increase the performance of the the textured dysprosium poles: operate the undulator at lower temperature, use thinner foils in the poles, and increase the complexity of the design of the undulator by installing backing magnets on the side of the poles opposite the magnetic gap. Because of those observations, all foils created subsequently have been 25 μm thick. Since that previous publication we have found evidence of another feature of the textured dysprosium that will influence future magnetic designs, namely that the direction of rolling affects the orientation of the easy axes of magnetization. Unfortunately, because cryogenic magnetic measurement techniques below 77 K require the use of liquid helium, we have had difficultly finding facilities willing to perform these measurements until recently.

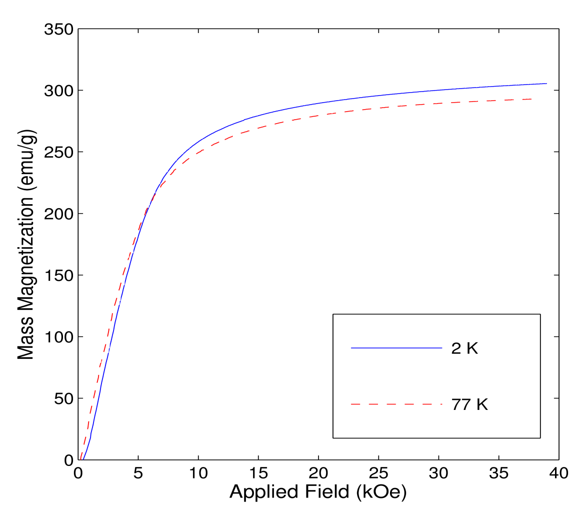

Figure 1: Comparison of the magnetic performance of textured dysprosium at 2 K and 77 K. The sample was cut such that the direction of measurement was within the rolling plane.

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Temperature Effects

The first suggested solutions is to decrease the temperature of the device. A colder undulator would have both higher remanent magnetic field of the PrFeB magnets [4, 5] and higher initial permeability in the textured dysprosium poles. The former results in larger applied fields while the latter results in greater pole tip field per unit of applied field, both critical to attaining large on-axis magnetic fields [6]. Figure 1 shows a comparison between the magnetization of textured dysprosium at 2 K and 77 K. The two features of note are that above 5 kOe applied field, the colder textured dysprosium is more strongly magnetized and below 5 kOe, the warmer sample is more strongly magnetized. We would expect that as the material is cooled, it is more easily magnetized because the thermal energy that allows the individual dipoles to resist the torque of the applied field is reduced [7]. That appears to be the case at larger applied field (>10 kOe), but not lower applied field.

The shape of the measured sample in Fig. 1 was modified from the original shape to fit into the measurement device. The modification resulted in a large demagnetizing factor [8]. Because of this we hypothesize that the unexpected reversal of performance below 5 kOe can be explained by the effect of the large demagnetizing factor. At low applied field, we would expect that the actual applied field would be lower than the observed applied field, which is the abscissa of Fig. 1, in the case of stronger magnetization because the two are related as $H_{actual} = H_{observed} - NM$, where N is the demagnetizing factor and M is the magnetization of the sample.

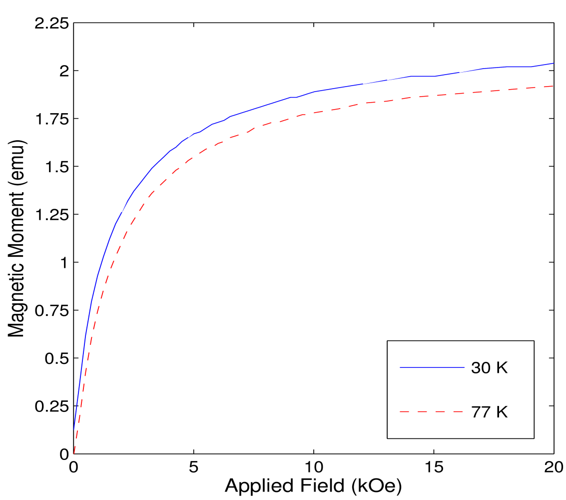

Figure 2: Comparison of the magnetic performance of textured dysprosium at 30 K and 77 K. The sample was cut such that the direction of measurement was within the rolling plane. Note the different ordinate as compared to Fig. 1.

To test this hypothesis, a different sample, manufactured identically and of smaller demagnetizing factor, was measured in a different measurement setup at a different location. The results of the measurements at 30 K and 77K, after correction for the demagnetizing factor, are shown in Fig. 2. It can be seen that the lower temperature magnetization curve always shows higher magnetization than the higher temperature curve, consistent with the hypothesis of a large demagnetizing factor in the measurement shown in Fig. 1 We chose to perform the second measurement at 30 K, instead of the previous 2 K, because that temperature can be maintained by a closed loop cold head, reducing future experimental complexity. 30 K is also the approximate temperature of maximum thermal conductivity of copper [9].

Orientation Effects

In previous simulation work, we have treated textured dysprosium as an anisotropic material with one hard axis, [0001], and two easy axes, $<10\bar{1}0>$ and $<11\bar{2}0>$. This is because the available simulation packages can only handle anisotropy of this 2+1 form [10]. The assumption is that there is an equal mixture of the two easy domains in the plane of the foil (the basal plane). However, the two easy axes are not equivalent, the $<10\bar{1}0>$ axis is actually harder than the $<11\bar{2}0>$ axis, even though both are much softer than the [0001] direction [11, 12]. Therefore, if the process that generates texture produces a preference for grain orientation, there will be a preferred direction for cutting the poles out of the bulk laminated material. The highest on-axis magnetic field will be obtained if the pole is manufactured such that the $<11\bar{2}0>$ axis is normal to the undulator mid-plane. This is, of course, a statement of the average direction in which each axis points.

Previous work studying textured dysprosium has observed that the texture develops such that the $<10\bar{1}0>$ axis is preferentially aligned with the direction of rolling [13]. We should, therefore, be able to detect this difference in measurements made on samples cut from the two different orientations. To measure the difference in magnetization, two samples were cut from the same piece of bulk laminated pole, called sample A and sample B. Sample A was measured along the direction of rolling and sample B was measured along the direction perpendicular to the rolling direction and the foil normal. As can be seen in Fig. 3, sample A is clearly magnetically harder than sample B, consistent with previous observations showing a preference for the texture to develop with the $<10\bar{1}0>$ axis along the direction of rolling. Both samples are more easily magnetized at lower temperature and the benefits of cooling the textured dysprosium to 30 K are almost entirely erased by non-optimal orientation of the texture relative to the undulator mid-plane.

Simulation has shown that, in a hybrid undulator design of 7-9 mm period length, the applied field at the pole tips is approximately 0.15 T. At this applied field, the remanent field of the textured dysprosium is 25% larger for a pole cooled to 30 K and cut such that the $<11\bar{2}0>$ axis is optimally oriented, as compared to a pole cooled to 77

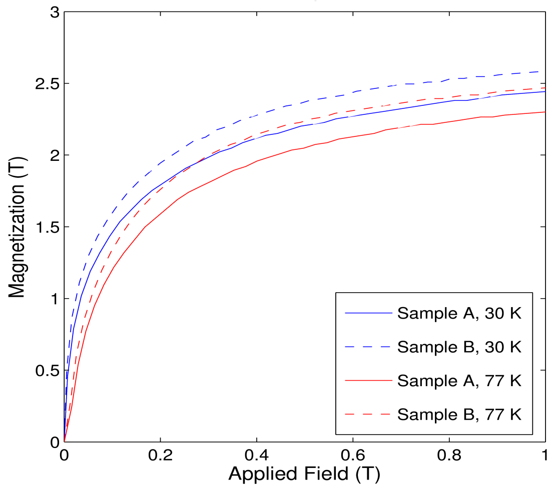

Figure 3: Comparison of the magnetic performance of textured dysprosium as a function of measurement along the two axes of the basal plane, <10$\bar{1}$0> (sample A) and <11$\bar{2}$0> (sample B), at two different temperatures.

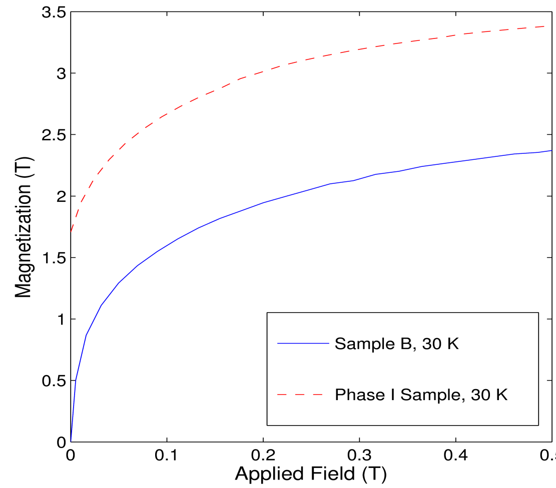

Figure 4: Comparison of the easy magnetization curves from the current sample B and the data presented in Ref. [2]. The decrease in magnetic performance is due to increased oxide formation in the updated procedure for making the bulk laminate.

K and cut such that the <10$\bar{1}$0> axis is normal to the undulator mid-plane. In fact, this is a conservative estimate because the more easily magnetized material will apply a larger field at the pole tip.

Material Performance

It is clear from the preceding that the highest peak field will result from choosing sample B cooled to 30 K. By cutting the poles from the bulk laminate such that the <11$\bar{2}$0> axis of the texture is oriented in the same direction as the dominant magnetic field. For example, in a vertically ($\hat{y}$) polarized planar undulator in which and electron in the mid-plane oscillates horizontally ($\hat{x}$) and the beam travels along the $\hat{z}$-direction, the texture of the dysprosium should be oriented such that ($\hat{x}$,$\hat{y}$,$\hat{z}$):([0001],<11$\bar{2}$0>,<10$\bar{1}$0>) for optimal performance. Previous simulation has shown that there is a small decrease in performance when the texture is oriented with the $\hat{x}$ and $\hat{z}$ directions switched, poles with this texture orientation are much easier to manufacture.

To more efficiently produce a large amount of bulk laminate textured dysprosium, we modified the processing technique that produced excellent magnetic results in earlier phases of the project. The principal modification was an intermediate annealing step during rolling to relieve strain from the rolling. Although x-ray 2θ scans of the material show good texture development [1], this additional step substantially increases the fraction of the bulk laminate that is made up of dysprosium oxide, reducing overall magnetic performance. This additional annealing step has been removed from the process and additional measurements are being performed at the time of publication.

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