Nuclear Instruments and Methods in Physics Research A 735 (2014) 521–527

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Textured dysprosium and gadolinium poles for high-field, short-period hybrid undulators

Alex Murokh [a], Vyacheslav Solovyov [b], Ron Agustsson [a], Finn H. O'Shea [a,c,*], Oleg Chubar [b], Yung Chen [a], Thomas Grandsaert II[a]

[a] RadiaBeam Technologies, Inc, 1717 Stewart St., Santa Monica, CA 90404, United States
[b] Brookhaven National Laboratory, Upton, NY 11973, United States
[c] Department of Physics, University of California, Los Angeles, CA 90095, United States

ARTICLE INFO

Article history:
Received 10 July 2013
Received in revised form
8 October 2013
Accepted 8 October 2013
Available online 16 October 2013

Keywords:
Dysprosium
Undulator
Material science

ABSTRACT

We discuss the feasibility of enhancement of the gap field in a short-period hybrid undulator by using pole inserts with the saturation inductance B_s, over that of iron, 2 T. Dysprosium metal, with the saturation inductance of 3.4 T below 90 K, and Gadolinium with $B_s=2.7$ T, appear as good candidates as the optimized pole material. However, due to the high magnetic anisotropy of Dy, such a high level of magnetization can only be realized when the external field lies in the basal plane. This implies that the pole has to be single-crystalline or highly textured. Considering that growing large, >10 mm, Dy single crystals is difficult, we propose secondary recrystallization as a method to induce the required texture in thin Dy and Gd foils. The textured foils can be stacked to produce pole inserts of the desired geometry and orientation. Results of small-scale processing and magnetic measurements of thin (20–60 μ) foils provide evidence that the required texture quality can be achieved by a relatively simple sequence of heat-treatments and cold rolling. The advantage of textured Dy and Gd poles is demonstrated in a several period test undulator.

1. Introduction

Discovery of high-flux rare-earth-iron–boron permanent magnets in 80s [11] enabled development of short-period, high field undulators. Today, the majority of undulators are designed as the so-called Halbach arrays [9], of which the hybrid design can be described as a sequence of opposing permanent magnets separated by soft ferromagnetic poles. Combination of Nd–Fe–B permanent magnet with the remnant induction Br=1.2 T [11] and Vanadium-Permendur [5] poles with the saturation induction $B_s=2.3$ T allows achieving 1.3 T peak gap field with a gap-to-period ratio of 0.4. Incremental but steady improvement of the remnant induction, accelerated with the introduction of cryo-cooled Pr–Fe–B magnets [10], raises a question whether iron-based poles are still adequate for the modern high-field, short period undulators.

Dysprosium metal has the saturation inductance of 3.8 T at 4.2 K. Relatively high Curie temperature, 90 K, makes Dy suitable for magnetic applications below 77 K, either as a part of a cryo-cooled permanent magnet array or a superconducting undulator. Rare earth poles made from polycrystalline Holmium and Dysprosium have been used to augment magnetic flux in superconducting magnets [1,4] and undulators [8]. Due to low magnetic permeability of these poles, a measurable flux gain is possible only in a superconducting system. The field strength in a permanent-magnet system is on the order of 10 kOe, therefore a useful pole should have initial permeability over 10.

Dysprosium has a hexagonal close packed (hcp) structure [18], schematically shown in Fig. 1(a). This type of structure imposes strong anisotropy on the magnetic properties of the material: dysprosium has very hard direction along [0001] (normal to the basal plane), followed by the moderately hard $\langle 10\bar{1}0\rangle$ and easy $\langle 11\bar{2}0\rangle$ directions [2,6]. A polycrystalline Dy sample, which is composed of randomly oriented crystallites, would be a very hard ferromagnet with an apparent saturation in moderate magnetizing fields, <10 kOe, well below the saturation induction of the single crystal. To realize the advantage of Dy over a well-established Vanadium-Permendur (V-P) material in a permanent magnet based undulator, one needs a crystallographically oriented Dy pole so that the magnetizing field is directed along the easy axis or, at least, in the basal plane. A straightforward solution would be cutting the pole from a single crystal. However, small size of the available crystals and the expensive equipment involved in the process make this route most likely impractical. Gadolinium metal has an identical hcp structure, however, it is magnetically softer

* Corresponding author at: RadiaBeam Technologies, Inc, 1717 Stewart St., Santa Monica, CA 90404, United States. Tel.: +1 310 822 5845.
E-mail address: oshea@radiabeam.com (F.H. O'Shea).

0168-9002/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nima.2013.10.020

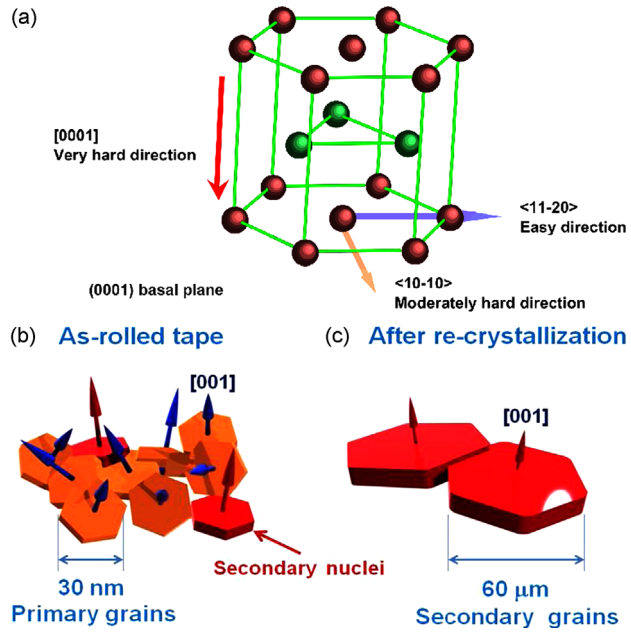

Fig. 1. (a) Crystal structure of Dy metal showing principal magnetization directions. Schematic illustration of the secondary recrystallization process: better oriented primary grains become nuclei of large secondary grains consuming misoriented primary grains (b). This results in quasi-crystalline structure of the recrystallized tape (c).

than Dysprosium. The easy magnetization direction of Gd is tilted at about 30° with respect to the (1000) direction [14]. The disadvantage of Gd is relatively low saturation magnetization, 2.7 T, however, higher permeability values can be more readily attained as compared to Dy.

Secondary recrystallization offers a scalable way to manufacture textured foils of various metals. The process is widely used to induce texture in rolled foils of fcc metals, such as Ni [15], Al, Fe–Si alloys [16]. In the early 1970s Westinghouse research group suggested the secondary recrystallization process to manufacture large-scale Dy foils [21]. Fig. 1(b) and (c) is a simplified illustration of secondary recrystallization process. A cold-rolled Dy tape is polycrystalline, composed of small (<100 nm) primary Dy grains, Fig. 1(b). Some grains have favorable orientation, with [001] direction parallel to the tape normal and the fast-growth ab-plane parallel to the tape face. The better oriented grains gain a small energetic advantage over other grains, which becomes amplified as the grains start to grow during the subsequent annealing. During the annealing the secondary grains expand rapidly, consuming misoriented primary grains through the so-called abnormal grain growth mechanism [12]. At the end of this processing step, only very large (>10 μm), well-oriented secondary grains remain, Fig. 1(c).

In this work we analyze feasibility of using recrystallized Dy and Gd foils as poles of a cryo-cooled hybrid undulator. We show that secondary recrystallization can be used to produce textured foils suitable for the pole application.

2. Experiment

2.1. Synthesis of textured Dy and Gd poles

Dysprosium foils were produced by sequential cold rolling of Dy ingots until the foil thickness was reduced to 25–100 μm. The foils were annealed in vacuum (10^{-6} Torr) in a quartz tube furnace at 1100–1200 °C for 10–20 min. The tube was evacuated by a diffusion pump with a liquid nitrogen cold trap. The difficulty with annealing dysprosium metal is very high reactivity, which is explained by low free energy of Dy_2O_3. Due to such a low value of free energy, Dy metal can oxidize by reducing quartz to silicon, therefore a very expensive ultra-high vacuum annealing system is typically required. To avoid oxidation of the foils during annealing at relatively low vacuum pressure, they were enclosed in a specially designed molybdenum annealing cell. The cell restricted flow of oxygen to the surface of the Dy foil so that Dy vapor, present at these temperatures, reacted with the entering oxygen creating local ultra-high vacuum environment. As a result the foils had clean and shiny surfaces with only minor surface oxidation. The foil structure was analyzed using a four-circle X-ray diffractometer. Magnetic properties of foils were measured by a superconducting magnetometer in external field up to 7 T.

A laminated piece was assembled by pressing the Dy foils into a 2 mm composite and subsequent annealing of the piece at 1100 °C in vacuum. After this treatment the foils fused into a solid block with the density over 98% of bulk Dy. The 12×1.6 mm^2 test poles were machined from the block to exact dimensions of existing V-P poles.

A similar rolling–annealing procedure was employed to manufacture Gd poles.

2.2. Two-period undulator testing

The two-period undulator consisted of a pair of jaws held together by a strong back that serves to both define the magnetic gap and secure the undulator to the test bench. The entire assembly is made out of copper to minimize thermal gradients. The main part of the jaw is a precision-machined block that contains a series of grooves that alternately hold magnets and poles. As the stable magnetic lattice applies a force on the magnets that pushes them into the copper block, no additional restraint of the magnets is necessary. To maximize the thermal contact with the copper structure the grooves are made as deep as possible. The first step in the jaw assembly is placing in the poles and then securing them with the keepers. Next the magnet grooves are coated with thermally conducting cryogenic-compatible grease. The jaw piece and the magnets are cooled to -20 °C and the magnets are inserted into the lattice. PrFeB magnets are used, because they do not show a spin axis reorientation (SAR) between 77 K and room temperature, unlike NdFeB magnets [3]. As these magnets have larger remanent field than samarium–cobalt magnets (which also do not show an SAR in the given temperature range), they were chosen to maximize the field applied to the poles. The magnets are cooled before insertion because the magnets see the largest reverse fields during magnet insertion [17]. After the magnets are safely in the lattice, the reverse fields are low enough that the magnets are safe at room temperature. Once the jaws are assembled they are bolted to the copper strong back to define the 2.5 mm gap. The *c*-axis of the textured dysprosium poles was oriented in the horizontal direction (see Fig. 2). The partially assembled test undulator is shown in Fig. 2(a).

A test stand with a small area scanning Hall probe was designed to measure the central magnetic field at cryogenic temperature, Fig. 2(b). The entire setup was placed within an insulated enclosure to minimize convective heating. This baseline design was tested with a low temperature thermocouple probe and demonstrated that we could maintain a sufficient LN_2 bath for $\sim$20 min.

The test undulator consists of two jaws, each containing 5 poles and 6 magnets; five of the poles in one jaw can be seen in Fig. 2. For each rare-earth material, two measurements of the test undulator are made at 77 K. In the first measurement, all of the