4-25-2006

Highly coercive rapidly solidified Sm–Co alloys

Shampa Aich
University of Nebraska - Lincoln, saich2@unl.edu

V.K. Ravindran
University of Nebraska - Lincoln

Jeffrey E. Shield
University of Nebraska - Lincoln, jshield2@unl.edu

Follow this and additional works at: http://digitalcommons.unl.edu/cmrafacpub

Part of the Nanoscience and Nanotechnology Commons

Aich, Shampa; Ravindran, V.K.; and Shield, Jeffrey E., "Highly coercive rapidly solidified Sm–Co alloys" (2006). Faculty Publications from Nebraska Center for Materials and Nanoscience. Paper 7.
http://digitalcommons.unl.edu/cmrafacpub/7

This Article is brought to you for free and open access by the Materials and Nanoscience, Nebraska Center for (NCMN, formerly CMRA) at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Faculty Publications from Nebraska Center for Materials and Nanoscience by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.
Highly coercive rapidly solidified Sm–Co alloys

S. Aich, a) V. K. Ravindran, and J. E. Shield
Department of Mechanical Engineering and Center for Materials Research and Analysis, N104, WSEC, University of Nebraska, Lincoln, Nebraska 68588

(Submitted 31 October 2005; published online 25 April 2006)

Highly coercive (\(H_c\) up to 37 kOe at 300 K), high remanent permanent magnets have been achieved by rapid solidification of binary Sm–Co alloys and Sm–Co alloys modified with Nb and C. Rapidly solidified SmCo\(_x\) alloys with \(x\) ranging from 5 to 11.5 formed predominantly a solid solution TbCu\(_7\)-type SmCo\(_7\) phase, although hcp Co was observed for \(x > 7.3\). A coercivity value of 10 kOe was observed for \(x < 6.1\), even though the microstructural scale was on the order of 1 \(\mu m\). The coercivity decreased significantly with the presence of the hcp Co phase, which formed initially as \(\sim 80\) nm grains and, at higher \(x\), as primary dendrites. Additions of 3 at. \% Nb or 3 and 5 at. \% C profoundly affected the coercivity values. Transmission electron microscopy (TEM) investigations revealed the origin of the improved coercivity. The addition of Nb resulted in a significant reduction in microstructural scale. The SmCo\(_7\) grain size decreased systematically with Nb content, reaching 150–200 nm at 3 at. \% Nb. The addition of C also significantly enhanced the coercivity, which systematically increased with C content and reached 37 kOe at 5 at. \% C. The effect of C, however, resulted in morphological changes as TEM revealed the formation of an intergranular phase that effectively isolated the hard magnetic SmCo\(_7\) grains from one another, reducing magnetic interactions. Excellent isotropic energy products of 6–8 MGOe were also achieved. © 2006 American Institute of Physics. [DOI: 10.1063/1.2173238]

INTRODUCTION

There is a great deal of interest in developing coercivity in Sm–Co-based permanent magnets through simpler processing. For example, rapid solidification effectively forms the TbCu\(_7\)-type metastable structure from which precipitation-hardened magnets derive their microstructures upon appropriate heat treatment.\(^1\)\(^-\)\(^^4\) Efforts to produce improved magnetic properties in as-solidified Sm–Co alloys would eliminate the need for additional processing. Very high coercivity (~40 kOe) was observed in melt-spun Sm–Co.\(^5\)\(^\)\(^6\) These alloys, however, relied on significant amounts of alloying additions to produce the proper solidification behavior necessary to obtain the high coercivity. Efforts to produce high coercivities without alloying additions have produced only modest results.\(^5\)\(^)\(^^\)\(^)\(^\)\(^)\(^\)\(^7\) Here, we have investigated the role of Sm/Co ratio on the magnetic properties and also reported significant improvements in coercivity with only minor alloying additions.

EXPERIMENTAL PROCEDURES

Three series of alloys have been examined in this study. The first series were simple binary Sm–Co alloys with varying Sm/Co ratios; these had a nominal composition of SmCo\(_x\), with \(x\) ranging from 5 to 11.5. The other series examined a fixed Sm/Co ratio with Nb or C additions, with nominal compositions of (SmCo\(_{2.3}\))\(_{100-\%}\), \(T_y\), where \(T = \text{Nb or C}\) and \(y = 3\) and 5. The alloys were made from high purity (>99.95\%) elemental constituents by arc melting in a high purity argon atmosphere. Before arc melting, 5\% extra Sm was added to the sample to compensate for loss due to Sm vaporization during melting. The ingot was then rapidly solidified by melt spinning in high purity argon at a chamber pressure of 1 atm and a tangential wheel velocity of 40 m/s.

The magnetic measurements were made by superconducting quantum interference device (SQUID) magnetometry at 300 K utilizing a Quantum Design MPMS with a maximum field of 7 T. Magnetic measurements were made on several ribbon pieces mounted so that the magnetic field was applied in the plane of the ribbon. Transmission electron microscopy was accomplished with a JEOL2100 operating at 200 kV. Electron transparency was achieved by mounting the melt-spun ribbon on a slightly polished Cu oval and by ion milling to perforation using a Gatan Duomill or precision ion polishing system (PIPS) at 4.5 kV. Structural characterization by x-ray diffraction was also conducted using a Philips diffractometer and Cu K\(\alpha\) radiation.

RESULTS AND DISCUSSIONS

X-ray diffraction and microscopic observation revealed that rapid solidification of the binary SmCo\(_x\) alloys with \(x\)
The magnetic properties were strongly dependent on the microstructures. In the binary (unalloyed) SmCo$_{7}$ alloys, the coercivity was significantly affected not so much on the Sm/Co ratio but on the phase formation. The lack of dependence on Sm/Co ratio was somewhat surprising, given the strong dependence of coercivity on the Sm/Co ratio in Sm–Co–Nb–C alloys. Here, a dramatic decrease in coercivity coincided with the formation of Co (Fig. 4). The ~80 nm fcc Co evidently enables reversal, which reduces the coercivity. Interestingly, the $x$=6.1 and 5.25 alloys had rather high coercivities, especially considering the rather coarse grains which may exceed the single-domain limit for these compounds.

The addition of 3 at. % Nb or C significantly improved the coercivity of the SmCo$_{7}$ with $x$=7.3 (Fig. 5). Additionally, the energy products were improved to 6–8 MGOe, excellent values for isotropic Sm–Co-based permanent magnets. The improved coercivity is due to the concomitant reduction in grain size. The increase in the C-added alloy is also due to the formation of the grain boundary phase, which effectively isolates the hard magnetic grains from one another. This is also readily evident in the alloy with 5 at. % C, which had a coercivity of 37 kOe. The dramatic increase here is due to the decreased magnetostatic interactions between the well-isolated SmCo$_{7}$ grains.

**CONCLUSIONS**

The binary SmCo melt-spin ribbons can achieve better microstructures and magnetic properties when modified with Nb and C additions. The addition of Nb helps to reduce the size of the (1:7) phase and thus helps to improve coercivity. The addition of C results in morphological changes in the microstructure which reveals the source of high coercivity, the isolated smooth interfaces. The intergranular region of...
the grain boundary contains a different phase that separates the grains and thus lowers the magnetostatic energy resulting in the higher coercivity.

ACKNOWLEDGMENTS

This project was supported by the National Science Foundation under Grant No. DMR0305354. The authors also benefited greatly from the shared facilities at the University of Nebraska’s Materials Research Science and Engineering Center, QSPINS, funded by the National Science Foundation. Support from the Nebraska Research Initiative is also greatly appreciated.