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13. ABSTRACT (Maximum 200 Words)  A scientific study has been concluded on the energy loss in advanced coated superconducting wires and tapes that arise from the presence of ferromagnetic substrate materials. Since Ni-W alloys are being used presently as substrates in prototype commercial conductors, a thorough investigation was conducted on the magnetic and loss properties of a series of $Ni_{1-x}W_x$ biaxially textured alloys, for the entire range of ferromagnetism, $x = 0 - 9$ at% W. The Curie temperatures and saturation magnetization decreased linearly with W-content to a critical concentration of 9.6 at% W. The ferromagnetic loss at cryogenic temperatures was investigated as a function of composition, processing variables, magnetic field amplitude, bending deformation, and cutting operations. These studies were conducted in cooperation with the Coated Conductor development program at the Oak Ridge National Laboratory, American Superconductivity Corp., and Oxford Instruments Superconducting Technology. More recently, investigations have been initiated to understand vortex pinning and the critical current density in thin superconducting layers on "RABiTS" substrates.				
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"Magnetic studies of substrate and superconductive materials for development of advanced  
coated conductors,"

1 July 2002 – 30 June 2004

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During the two-year duration of this grant, we have significantly advanced the understanding of ac losses in coated conductors based on high- $T_c$  superconductors. Special emphasis has been given to investigating the ac losses arising from ferromagnetic substrate and buffer layer materials, which are presently used in coated conductors based on the "RABiTS" technology (Rolling Assisted Biaxially Textured Substrates). This technology is employed by both American Superconductivity Corp. and Oxford Instruments Superconducting Technology in fabricating prototype "second generation" conductors with  $\text{YBa}_2\text{Cu}_3\text{O}_7$  as the superconductor of choice. Our research efforts have been coordinated with these companies and with R&D programs at the Oak Ridge National Laboratory. In the following are brief descriptions of investigations conducted during this grant; several have been published in the open literature and one project is still in progress.

An early study focused on the measurement and analysis of the transport alternating current (ac) loss [1] in state-of-the-art coated conductors that were fabricated by American Superconductor Corporation. Two different RABiTS-processed  $\text{YBa}_2\text{Cu}_3\text{O}_7$  (YBCO) tapes were measured at 77 K. Each contained a 1  $\mu\text{m}$  layer of YBCO with a 3  $\mu\text{m}$  silver cap layer, but two different nickel alloy substrates were used to assess their contribution to the overall ac loss. The substrates both had a 75  $\mu\text{m}$  thick base of Ni-5 at% W, but one also contained a 2  $\mu\text{m}$  nickel overlayer as part of the buffer layer architecture. Measurements of the ac loss showed two major components, one from superconductive hysteresis in the YBCO and one from ferromagnetic hysteresis in the substrates. For ac currents  $I$  near  $I_c$  (the critical current), superconductive losses dominated. These losses followed the Norris theory rather well. The loss from the substrates was measured separately using magnetic methods, for various ac field amplitudes. The study showed that the ferromagnetic loss exceeds that of the superconductor at lower levels of ac current, where  $I < 30\text{--}50\%$  of  $I_c$ . Overall, this work demonstrated that (1) a combined transport and magnetic study can provide a good understanding of the observed ac loss in present day, second generation coated conductors, (2) the hysteretic losses are additive, and (3) the *fractional* loss from the ferromagnetic substrate decreases for current levels approaching the critical current  $I_c$ .

A second project addressed the continuing topic of developing and characterizing coated conductors with high conductivity Cu-based substrates.[2, 4] Among the long term goals of this work are the development of conductor architectures that minimize hysteretic losses in substrate and buffer layer materials, the reduction of the costs of materials, and the stabilization of the overall conductor by providing parallel conduction channels that are closely coupled to a normal metal, most desirably the substrate *per se*. To achieve this, one must develop conductive buffer layers that preserve the biaxial texturing. A prototype tape architecture containing YBCO / (La-

Sr)MnO<sub>3</sub> / Ni / Cu was fabricated, for which the self-field current density at 77 K was  $2 \times 10^6$  A/cm<sup>2</sup>. While the Ni-layer prevented oxidation of the Cu substrate during processing, it also introduced ferromagnetic loss that was modest in magnitude, but not negligible. For applications, thinner and/or alloyed buffer layers and strengthened materials for substrates must be devised.

A third, major project was an investigation of substrate materials for RABiTS coated conductors.[3] Specifically studied were the magnetic and loss properties of several biaxially Ni<sub>1-x</sub>W<sub>x</sub> alloys, with tungsten contents  $x$  over the entire range of ferromagnetism, 0–9 at%. This alloy system has good strength and desirable compatibility with the usual conditions for materials fabrication. Ni-W materials were prepared by American Superconductor, Oxford, and the Oak Ridge National Laboratory. The Curie temperature and saturation magnetization were ascertained as a function of composition to replace old data of marginal quality from a study in the 1930's. We determined the ferromagnetic loss per field cycle by quasi-static magnetization measurements. This was done for a variety of magnetic field amplitudes that correspond to various peak ac currents in a conductor, or to an applied ac field. Also investigated was the increase in loss due to damage from 0.4 % bending deformations (such as that encountered in winding, cabling, etc.) and from cutting operations. The increase in loss due to cutting (measured in Ni-5 at%W materials) was significant; which is unfortunate as some potential processing routes would employ slitting for large-scale production of coated conductors. An additional finding was that the ac loss per cycle in low fields is independent of frequency to at least ~500 Hz, which includes the frequency range of airborne equipment for potential Air Force applications.

Cooperative work was initiated on the critical current density  $J_c$  in coated conductors on RABiTS, which were prepared by an ex-situ BaF<sub>2</sub> process. In particular, the dependence of the critical current on temperature, magnetic field, and film thickness were assessed. Specific objectives are to see whether  $J_c$  continues to increase as films are made thinner (perhaps enabling a very high performance multilayer conductor) and to determine the dominant form(s) of vortex pinning in these materials. This work is continuing in collaboration with the Oak Ridge National Laboratory.

Overall, the work in this program was conducted in close cooperation with the Coated Conductor development program at the Oak Ridge National Laboratory and cooperating organizations. Portions of the findings were presented as part of the DOE Coated Conductor Review in the summers of 2003 and 2004, and the reviewers' evaluation of the overall project were generally quite high. In summary, all of the objectives in the original grant proposal to AFOSR were achieved, and early results from further complementary investigations were obtained.

## PUBLICATIONS

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## PRESENTATIONS

- J. R. Thompson, "Coated conductors on textured Ni-Cr alloys with reduced ferromagnetism: substrate properties," International Workshop on Processing and Applications of Superconductors (Gatlinburg, TN, 1-2 August 2002).
- J. R. Thompson, A. O. Ijaduola, T. Aytug, A. Goyal, D. K. Christen, M. Paranthaman, D. M. Kroeger, and N. Rutter, "Magnetic Studies of Properties of Ni-based Substrates and Coated Conductors," DOE Wire Workshop, St. Petersburg, FL, 22 Jan 2003 (invited).
- J. R. Thompson, A. O. Ijaduola, A. Goyal, D.K. Christen, and D. M. Kroeger, "Magnetism and Ferromagnetic Loss in Ni-based Substrates for Coated Conductors," AFOSR HTS Coated Conductor Review, St. Petersburg, FL, 23 Jan 2003.
- J. R. Thompson, K.D. Sorge, L.A. Boatner, J.D. Budai, T.E. Haynes, Hwee Kwan Lee, A. Meldrum, T.C. Schulthess, C.W. White, and S.P. Withrow, "Nanoparticle arrays of Ni, Fe, Co, CoPt, and FePt: ion beam synthesis and competing magnetic energy scales," NANOMAT Congress 2003 (European Academy of Sciences, Brussels, 22-24 October 2003) (invited).
- A. O. Ijaduola, J. R. Thompson, A. Goyal, C. L. H. Thieme, and K. Marken, "Magnetism and Ferromagnetic Loss in Ni-W Textured Substrates for Coated Conductors," American Physical Society Meeting, Montreal, Canada, March 2004. *Bull. Am. Phys. Soc.* **49**, 137 (2004).
- J.R. Thompson, A. O. Ijaduola, A. Goyal, C. L. H. Thieme, and K. Marken, "Magnetism and Ferromagnetic Loss in Ni-W and Ni-Cr Textured Substrates for Coated Conductors," ac Loss Workshop, Oak Ridge, TN (30 September 2004). (invited).

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