Final Report
**Development of Cryotribological Theories &
Application to Cryogenic Devices**
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Submitted by

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Introduction

One of major areas of research in the Magnet Technology Division of the MIT National Magnet Laboratory (later the Francis Bitter National Magnet Laboratory and since 1995 the Francis Bitter Magnet Laboratory) has been superconducting magnet—design, construction, and operation. The so-called “high-performance” superconducting magnets, which were begun to be built in the mid 1970s for accelerators and later for NMR and MRI magnets, suffered from premature quenches. The principal causes of these premature quenches were suspected to be caused by mechanical disturbances, specifically conductor motion in the “dry” winding or cracking of epoxy resin in the winding impregnated with epoxy resin to immobilize the conductor.

In 1978, a research program aimed specifically on frictional motion in the superconducting magnet winding environment—cryotribology—was initiated by this program’s PI in collaboration with Prof. Ernest Rabinowicz of the MIT Department of Mechanical Engineering. This new cryotribology research program was complemented from the outset by an acoustic emission (AE) project that was also initiated by the PI at the about same time to improve diagnostic technique for high-performance superconducting magnets suffering from premature quenches. By 1985 it was generally agreed in the magnet community that mechanical disturbances were the principal causes of failure in high-performance superconducting magnets and various techniques were introduced to minimize or even eradicate them. During this period the PI played a major role in achieving a clear understanding of the design and manufacturing intricacies of high-performance superconducting magnets and making these magnets operate much more reliably than heretofore possible.

Below are selected papers on mechanical disturbances in high-performance superconducting magnets by th PI and his collaborators *prior to* the start of the present project.

Y. Iwasa, R.S. Kensley, and J.E.C. Williams, “Frictional properties of metal-insulator interface,” *IEEE Trans. Magn.* MAG-15, 36 (1979).

R.S. Kensley and Y. Iwasa, “Frictional properties of metal-insulator surfaces at cryogenic temperatures, *Cryogenics* 20, 25 (1980).

E.S. Bobrov, J.E.C. Williams, M.W. Sinclair, and Y. Iwasa, “Mechanical training of impregnated superconducting solenoids,” *IEEE Trans. Magn.* MAG-17, 736 (1981).

M.W. Sinclair, O. Tsukamoto, and Y. Iwasa, “Acoustic emission from superconducting magnets and superconductors,” *IEEE Trans. Magn.* MAG-17, 1064 (1981).

R.S. Kensley, H. Maeda, and Y. Iwasa, “Frictional disturbances in superconducting magnets,” *IEEE Trans. Magn.* MAG-17, 1068 (1981).

O. Tsukamoto, M.F. Steinhoff, and Y. Iwasa, “Acoustic emission triangulation of mechanical disturbances in superconducting magnets,” *Proc. 9th Symp. Engr. Problems of Fusion Research* (IEEE Pub. No. 81CH1715-2 NPS), 309 (1981).

H. Maeda, J.F. Maguire, O. Tsukamoto, and Y. Iwasa, “Lorentz force induced strand motion in a superconducting cable,” *Proc. 9th Sym. Engr. Problems of Fusion Research* (IEEE Pub. No. 81CH1715-2 NPS), 623 (1981).

Y. Iwasa, “Conductor motion in the superconducting magnet — A review,” *Proc. Workshop on the Stability of Superconductors in Helium I and Helium II* (Inst. Refrigeration, Paris, France), 125 (1981).

- O. Tsukamoto and Y. Iwasa, "An acoustic emission technique to localize mechanical disturbances in superconducting magnets — A review," *Proc. Workshop on the Stability of Superconductors in Helium I and Helium II* (Inst. Refrigeration, Paris, France), 259 (1981).
- O. Tsukamoto, M.W. Sinclair, M.F. Steinhoff, and Y. Iwasa, "Origins of acoustic emission in superconducting wires," *Appl. Phys. Lett.* **38**, 718 (1981).
- O. Tsukamoto, J.F. Maguire, E.S. Bobrov, and Y. Iwasa, "Identification of quench origins in a superconductor with acoustic emission and voltage measurements," *Appl. Phys. Lett.* **39**, 172 (1981).
- R.S. Kensley, H. Maeda, and Y. Iwasa, "Transient slip behavior of metal/insulator pairs at 4.2 K," *Cryogenics* **21**, 479 (1981).
- O. Tsukamoto, H. Maeda, and Y. Iwasa, "Microslip-induced degradation in a braided superconductor," *Appl. Phys. Lett.* **39**, 918 (1981).
- O. Tsukamoto and Y. Iwasa, "Acoustic emission triangulation of disturbances and quenches in a superconductor and a superconducting magnet," *Appl. Phys. Lett.* **40**, 538 (1982).
- H. Maeda, O. Tsukamoto, and Y. Iwasa, "The mechanism of frictional motion and its effects at 4.2 K in superconducting magnet winding models," *Cryogenics* **22**, 287 (1982).
- H. Maeda and Y. Iwasa, "Heat generation from epoxy cracks and bond failures," *Cryogenics* **22**, 473 (1982).
- O. Tsukamoto and Y. Iwasa, "AE technology as a diagnostic and monitoring technique for superconducting magnets," *Proc. 6th Intl. AE Symposium Japanese Soc. Nondestructive Inspection* (1982).
- H. Maeda, O. Tsukamoto, and Y. Iwasa, "Mechanical disturbances in superconducting magnet," *Proc. 9th Intl. Cryogenic Engr. Conf.* (Butterworth and Co., England), 543 (1982).
- Y. Iwasa, "Diagnostic requirements and mechanical disturbances in superconducting magnets," *Proc. 9th Intl. Cryogenic Engr. Conf.* (Butterworth and Co., England), 808 (1982).
- O. Tsukamoto and Y. Iwasa, "An acoustic emission technique to localize mechanical disturbances in superconducting magnets," *Proc. 9th Intl. Cryogenic Engr. Conf.* (Butterworth and Co., England), 827 (1982).
- Hideaki Maeda, Osami Tsukamoto, and Yukikazu Iwasa, "Mechanical disturbances in superconducting magnet (I)—Mechanism and effect of the frictional disturbances, *Teion Kogaku* (Japanese) **18**, 57 (1983). [The Oyama Memorial Award of the Japan Cryogenic Engineering Society for the best paper published in the *Teion Kogaku* (in Japanese) during 1983.]
- H. Maeda and Y. Iwasa, "Mechanical disturbances in superconducting magnet (II)—Epoxy cracking or debonding in an epoxy impregnated magnet, *Teion Kogaku* (Japanese) **18**, 70 (1983).
- Hideaki Maeda, Noriharu Tamada, Osami Tsukamoto, and Yukikazu Iwasa, "Mechanical disturbances in superconducting magnet (III)—Lorentz force induced strand motion in bundle conductor," *Teion Kogaku* (Japanese) **18**, 76 (1983).
- O. Tsukamoto and Y. Iwasa, "Sources of acoustic emission in superconducting magnets," *J. Appl. Phys.* **54**, 997 (1983).
- O. Tsukamoto and Y. Iwasa, "Mechanical disturbances in Rutherford-type and braid conductors," *IEEE Trans. Magn.* **MAG-19**, 443, (1983).
- K. Jacob, Y. Iwasa, J.W. Lue, and J.R. Miller, "Acoustic emission monitoring of LCP superconducting magnets," *Proc. 10th Symp. Fusion Engr. IEEE Cat. No. 83 CH1916-6 NPS*, 754 (1983).

Y. Yasaka and Y. Iwasa, "Stress-induced epoxy cracking and energy release at 4.2 K in epoxy-coated superconducting wires," *Cryogenics* 24, 423 (1984).

H. Fujita, T. Takaghi, E.S. Bobrov, O. Tsukamoto, and Y. Iwasa, "The training in epoxy-impregnated superconducting coils," *IEEE Trans. Magn.* MAG-21, 380 (1985).

O. Tsukamoto and Y. Iwasa, "Epoxy cracking in the epoxy-impregnated superconducting winding: Nonuniform dissipation of stress energy in a wire-epoxy matrix model," *IEEE Trans. Magn.* MAG-21, 377 (1985).

Y. Iwasa, "Experimental and theoretical investigation of mechanical disturbances in epoxy-impregnated superconducting coils. Part 1: General introduction," *Cryogenics* 25, 304 (1985).

E. S. Bobrov, J. E. C. Williams, and Y. Iwasa, "Experimental and theoretical investigation of mechanical disturbances in epoxy-impregnated superconducting coils. Part 2: Shear-stress-induced epoxy fracture as the principal source of premature quenches and training — theoretical analysis," *Cryogenics* 25, 307 (1985).

Y. Iwasa, E. S. Bobrov, O. Tsukamoto, T. Takaghi, and H. Fujita, "Experimental and theoretical investigation of mechanical disturbances in epoxy-impregnated superconducting coils. Part 3: Fracture-induced premature quenches," *Cryogenics* 25, 317 (1985).

H. Fujita, T. Takaghi, and Y. Iwasa, "Experimental and theoretical investigation of mechanical disturbances in epoxy-impregnated superconducting coils. Part 4: Prequench cracks and frictional motion," *Cryogenics* 25, 323 (1985).

Hiroyuki Fujita and Yukikazu Iwasa, High-resolution experimental techniques for cryomechanics — a study of mechanical behavior of materials at 4.2 K, *J. Experimental Mechanics* 26, 128 (1986). [The 1987 Hetenyi Award of the Society for Experimental Mechanics for the most outstanding research paper published in the *J. Experimental Mechanics* in 1986.]

Encouraged with a remarkable progress we had made in understanding mechanical behavior of superconducting magnets and left with a set of excellent tribometers that the PI had constructed, Prof. Rabinowicz and the PI decided to start a "cryotribology" project dedicated specifically to: 1) advance the theoretical understanding of low-temperature sliding behavior; 2) expand the cryogenic tribology data base; and 3) train graduate students in tribology, cryogenic engineering, and superconducting magnet technology. This program supported our cryotribology research from 1985 through 1999.

Achievements

Overall Key overall achievements of the project may be summarized below.

- Based on our exhaustive experimental results of the sliding behavior of materials at cryogenic temperatures, we conclude that the adhesion theory of friction and wear remains applicable at cryogenic temperatures.
- The attainment of absolutely stable, positive friction-velocity characteristics appears improbable at cryogenic temperatures due to the lack of materials which demonstrate strain-rate-dependent interfacial shear creep.
- Generation of cryotribological data for materials pairs used in superconducting magnets and cryogenic devices.
- Training of students in the fields of cryotribology, cryogenic engineering, and superconducting magnet technology.

Specific Specific conclusions drawn from the project's results are as follows.

- The adhesive friction theory suggests several alternatives for limiting this unstable first slip characteristic. The first relies on the use of relatively inert materials to reduce the asperities' tendency towards strong interfacial bonding. A frequently used method for reducing a polymer coating's tendency towards strong adhesive is to co-polymerize the coating with about 2~5% of a perfluorocarbon intermediate to reduce its surface energy. The perfluorocarbon intermediates typically migrate to the surface of the coating, thus providing a low-friction surface layer, while leaving the balance of the coating's bulk mechanical properties relatively intact.
- A second method for reducing the tendency towards unstable slip is to minimize transient interfacial junction growth. For instance, flexible ceramics and cuprous sulphide coatings have been examined as insulators for wind and react Nb_3Sn conductors. Because the softening point for these insulators is markedly higher than that for conventional polymeric insulators, their tendency towards transient room-temperature creep should be greatly reduced. Hence, these inorganic insulators offer the potential advantages of being harder, more creep resistant, and less surface active than conventional polymer-based coatings; these factors should all contribute to more stable sliding initiation. An added advantage to inorganic insulators is that their transverse thermal conductivity is at least an order of magnitude larger than that for a conventional organically insulated wire. This higher transverse conductivity should further improve stability by increasing the minimum propagating zone volume, and hence, the coil's minimum quench energy.
- An approach towards frictional stabilization is to use the conductor tension during manufacture to regulate the winding's effective axial stiffness. Abrupt conductor motions can occur on a variety of dimensional scales. In tightly-wound solenoids, the high static friction forces provided by the conductor tension effectively pin the conductors in their as-wound positions. However, statistical variations in the conductor thickness produce short segments that are not well supported. Because of their moderate stiffness these segments frequently shift back-and-forth between equilibrium positions as the magnet is charged and discharged. The recurrent motion of these segments during magnet training frequently prevents the magnet from ever reaching its designed operating current.

The effective axial stiffness of the individual turns in a loosely wound magnet are quite low in comparison. By proper preprogramming of the winding tension, the conductor turns can be made to shift to more stable equilibrium positions while the magnet is far from its critical surface. Because their axial stiffness is so low, the turns tend to retain their new equilibrium positions during subsequent charging cycles, hence, loose-wound magnets tend to train progressively as the conductors gradually shift to a more stable winding arrangement. As the inter-conductor gaps are removed from the winding its effective axial stiffness increases to a level comparable with that of a similarly configured epoxy-impregnated winding. Winding approach must aim to achieve impregnated winding reliability in a dry-wound magnet by allowing the winding to seek a natural, electromagnetically-compacted shape from the start of its energization cycle.

- A review of existing material properties at cryogenic temperatures, primarily time- and temperature-dependent hardness data, indicates a virtual elimination of rate-dependent deformation at liquid helium temperatures. Most reference sources indicate that the strain-rate dependencies that we desire are typically observed only above $0.4 - 0.5T_m$, where T_m is melting temperature. Thus, based on our present understanding of the materials-based frictional stabilization approach, even a coating of solid hydrogen, with $T_m = 14\text{ K}$, would be insufficient for stabilizing wire motions in a helium cooled superconducting magnet operating at 4.2 K .

List of Published Papers & Theses Generated on Cryotribology

Benneth F. Sarfo, *Creep of Polytetra-fluoroethylene (PTFE) at Room Temperature* (S.B. Thesis, June 1986; unpublished).

Ronald K. Gibson, *Tensile Creep of PTFE, G-10CR, and Copper at Room Temperature and 77 K* (S.M. Thesis, June 1987; unpublished).

John P. Voccio, *Experimental and Theoretical Study of Fracture Energy in a Glass-Epoxy Composite at 77 K* (S.M. Thesis, June 1987; unpublished).

Dawood Aized, *Sliding Behavior of Material Pairs at Room Temperature and at Cryogenic Temperatures* (S.M. Thesis, August 1988; unpublished).

Kevin P. Coleman, *Friction and Wear of Polymers at Cryogenic Temperatures* (S.B. Thesis, May 1989; unpublished).

T. Ohara, K. Agatsuma, K. Kaiho, T. Onishi, and Y. Iwasa, "Cryogenic microstrain measurement using laser light interference," *Cryogenics* **29**, 1050 (1989).

Robert K. Miller, *The measurement of Fracture Induced Dissipative Energies at 4.2 K* (S.M. Thesis, June 1990; unpublished).

S. Fuchino and Y. Iwasa, "A cryomechanics technique to measure dissipated energies of $\sim 10\text{ nJ}$," *Experimental Mechanics* **30**, 356 (1990).

T. Ohara, M. Umeda, K. Agatsuma, S. Kosaka, and Y. Iwasa, "Cryogenic creep measurement system using laser light interference," *Adv. Cryogenic Engr.* **35**, 1601 (1990).

P.C. Michael, D. Aized, Y. Iwasa, and E. Rabinowicz, "Mechanical properties and static friction behavior of epoxy mixes at room temperature and at 77 K," *Cryogenics* **30**, 775 (1990).

P.C. Michael, E. Rabinowicz, and Y. Iwasa, "Friction and wear of polymeric materials at 293, 77, and 4.2 K," *Cryogenics* **31**, 695 (1991).

S. Nishijima, T. Okada, P.C. Michael, and Y. Iwasa, "Friction and wear of a three-dimensional fabric-reinforced plastic at room temperature and liquid nitrogen temperature," *Adv. Cryogenic Engr.* **37A** (1992).

Y. Iwasa, "Mechanical disturbances in superconducting magnets—a review (invited plenary talk)" *IEEE Trans. Magn.* **28**, 113 (1992).

Philip C. Michael, *Cryotribological Investigation of Sliding Motion Emphasizing Mechanical Behaviors of High-Performance Superconducting Magnets* (Ph.D., June 1992; unpublished).

P.C. Michael, E.S. Bobrov, Y. Iwasa, and M. Arata, "Stabilization of dry-wound high-field NbTi solenoids," *IEEE Trans. Appl. Superconductivity* **3**, 316 (1992).

Yukikazu Iwasa, *Case Studies in Superconducting Magnets*, (Plenum Press, New York, 1994).

Philip C. Michael, Yukikazu Iwasa, and Ernest Rabinowicz, "Reassessment of cryotribology theory," *Wear* 174, 163 (1994).

Thomas M. Willet, *Cryotribology of Diamond Film Coated Silicon Disks Against Metals, Ceramics, and Natural Diamond* (S.M. Thesis, May 1995; unpublished).

M. Arata, P.C. Michael, and Y. Iwasa, "Stabilization of dry-wound high-field superconducting magnet by controlling frictional spring force," *IEEEJ Trans. D* (1995).

Thomas M. Willet, *Cryotribology of Diamond Film Coated Silicon Disks Against Metals, Ceramics, and Natural Diamond* (S.M. Thesis, May 1995; unpublished).

Philip C. Michael, Yukikazu Iwasa, and Ernest Rabinowicz, "Thermal activation in boundary lubricated friction" *Wear* 194, 218 (1996).

Ahmet F. Ashaboglu, *Cryotribology of Graphite and Diamond* (S.M. thesis, February 1996; unpublished).

Yukikazu Iwasa, A.F. Ashaboglu, and E.R. Rabinowicz, "Cryotribology of diamond and graphite," *Cryogenics* 37, (1997).

During the final 3 years of the program, between 1997 and 1999, our effort was focused on, with the permission of Program Director, Dr. Robert Price of the Division of Engineering and Geosciences, Office of Basic Energy Sciences, DOE, study of "active" levitation involving high-temperature superconducting YBCO disks. Below is a list of selected papers published resulting from this period.

Yukikazu Iwasa and Haigun Lee, "'Electromaglev'—magnetic levitation of a superconducting disk with a DC field generated by electromagnets: Part 1 Theoretical and experimental results on operating modes, lift-to-weight ratio, and suspension stiffness," *Cryogenics* 37, 807 (1997).

H. Lee, M. Tsuda, and Y. Iwasa, "'Electromaglev' ('active-maglev') — magnetic levitation of a superconducting disk with a DC field generated by electromagnets: Part 2 Theoretical and experimental results on lift-to-weight ratio and lateral stiffness," *Cryogenics* 38, 419 (1998).

Y. Iwasa, M. Tsuda, H. Lee, K. Sawa, H. Horiuchi, K. Nishi, M. Murakami, K. Nagashima, T. Miyamoto, and H. Fujimoto, "A Large electromaglev ('active-maglev') system," *Advances in Superconductivity X* (Springer-Verlag, Tokyo, 1998), 1325.

Makoto Tsuda, Haigun Lee, and Yukikazu Iwasa, "'Electromaglev' ('active-maglev') — magnetic levitation of a superconducting disk with a DC field generated by electromagnets: Part 3 Theoretical results on levitation height and stability," *Cryogenics* 38, 743 (1998).

Y. Iwasa, H. Lee, M. Tsuda, M. Murakami, T. Miyamoto, K. Sawa, K. Nishi, H. Fujimoto, and K. Nagashima, "Electromaglev—levitation data for single and multiple bulk YBCO disks," *IEEE Trans. Appl. Supercond.* 9, 984 (1999).

Y. Iwasa, H. Lee, M. Tsuda, M. Murakami, T. Miyamoto, K. Sawa, K. Nishi, H. Fujimoto, and K. Nagashima, "Electromaglev—levitation data for single and multiple bulk YBCO disks," *IEEE Trans. Appl. Supercond.* 9, 984 (1999).

Makoto Tsuda, Haigun Lee, So Noguchi, and Yukikazu Iwasa, "'Electromaglev' ('active-maglev') — magnetic levitation of a superconducting disk with a DC field generated by electromagnets: Part 4 Theoretical and experimental results on supercurrent distributions in field-cooled YBCO disks," *Cryogenics* 39, 893 (1999).