Strain Effects in Superconducting Compounds

This paper [1] was presented by invitation at the 1983 International Cryogenic Materials Conference at a crucial point in the scale-up of superconductor magnet applications. It synthesizes a wide range of electromechanical strain data into what has become known as the Strain Scaling Law, which has had a strong impact on the design of large-scale, high-field superconductor magnet coils since that time. The Strain Scaling Law was the result of a unique high-field electromechanical measurement capability, developed by Jack Ekin at NBS, which led to the discovery and systematization of the intrinsic strain effect in practical superconductors.

In the years leading up to this work, it was known that superconductors have a "critical surface" that is a function of temperature, current density, and applied magnetic field. It had not been known that the critical surface also depends on an additional fundamental parameter, mechanical strain. Fig. 1 shows the scaling of the superconductor critical surface with this variable.

This discovery was especially important to the development of large-scale superconductor applications because early work had focused only on small coils of superconducting wire in which the magnetic forces were small. However, the need to handle large forces emerged with the development of large-scale magnets for particle accelerator machines, magnetic plasma confinement in fusion energy, superconducting magnetic energy storage (SMES), and medical magnetic resonance imaging (MRI) systems.

Ekin had focused primarily on the electrical properties of metals and superconductors in his thesis work at Cornell University and postdoctoral work at Rutgers University before joining NBS in 1975. The focus of his group at NBS was predominantly on mechanical properties, which led him to probe the unexplored niche between the electrical and mechanical research worlds. This coincidence of two fields of expertise ultimately resulted in the discovery of the superconductor strain effect and the Strain Scaling Law.

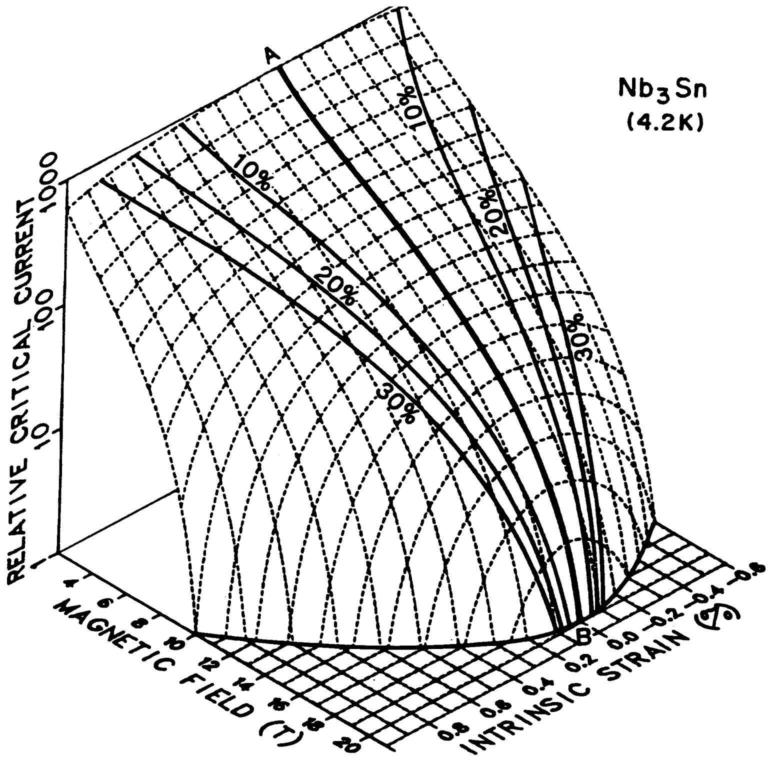

Fig. 1. *J-B-ε* critical surface for multifilamentary Nb_3Sn superconductors.

Prior work in this unique electromechanical field was scarce and had focused on small experimental samples of new superconducting materials, including thin films [2], monofilamentary wires [3], and single crystals [4]. However, the intrinsic non-hydrostatic strain effect was not measured in practical filamentary NbTi conductors until 1975, when the first measurements on the effect of strain on critical current (I_c) were reported by Ekin, Fickett, and Clark [5]. The interaction could not be explained simply by superconductor filament breakage, heating, or cross-sectional area reduction, but appeared to be intrinsic to the superconducting material itself.

About a year later, a much larger effect of strain on I_c was found in multifilamentary Nb_3Sn conductors by Ekin [6], Easton and Schwall [7], and McDougall [8]. This area of research then expanded when an accompanying strain effect was found for critical temperature T_c [9,10], as well as the upper critical field (B_{c2}) [11,12]. Ekin's systematic high-field measurements synthesized these effects into a strain scaling law that was first presented by him in a widely cited earlier paper in 1980 [13]. Then, in *Strain Effects in Superconducting Compounds,* he demonstrated that the Strain Scaling Law had wide applicability in virtually all practical high-field superconductors at the time. Fig. 2 is the first set of nearly universal curves showing the effect of strain on the upper critical field B_{c2} of the set of superconductors having the A-15 crystal structure. Each of these curves corresponds to the thick-line curve shown in the base plane of the critical surface in Fig. 1; they are the prime determinant of the entire superconductor critical surface.

The paper also presented the first strain-effect data on a relatively new superconductor, Nb_3Al. As seen in Fig. 2, Nb_3Al has a remarkably small strain effect in comparison with Nb_3Sn, the most widely studied superconductor of the day. This discovery of the relative strain insensitivity of Nb_3Al resulted in an international effort to produce this superconductor material commercially in practical lengths. That goal has been realized, and Nb_3Al is currently being explored for use in a new class of high-field magnets made using a much more efficient "react-and-wind" technique. These magnets are being developed for use in energy storage, high energy physics accelerators, and medical imaging systems.

Today, NIST continues to be the world leader in electromechanical measurement techniques, particularly since the advent of high-temperature superconductors, as well as the mechanical challenges inherent to these brittle ceramic oxide materials. Most superconductor applications are also being scaled up in size with an attendant increase in magnet stress, underscoring the

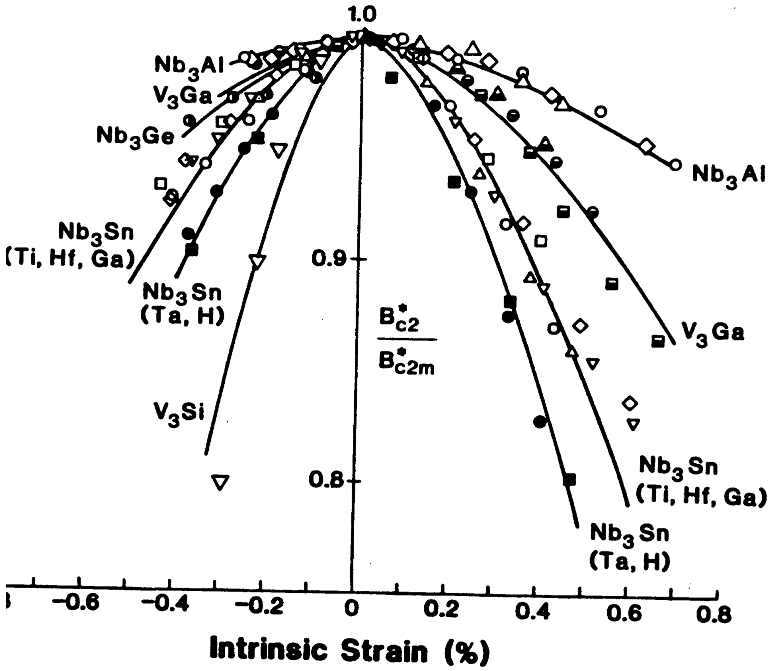

Fig. 2. Effect of uniaxial strain on the upper critical field of practical A-15 superconductors.

need for precise measurements of electromechanical performance. NIST measurement expertise is also sought for its third party independence in evaluating superconductor performance, particularly with the expansion of superconductor applications in the electric power industry, which is currently undergoing deregulation.

Jack Ekin was born in Pittsburgh, Pennsylvania, on August 31, 1944. He received a B.S. degree in physics from the University of Michigan, Ann Arbor, in 1966; a Fulbright Scholarship for beginning graduate study in physics at the University of Heidelberg; and a Ph.D. in solid state physics from Cornell University in 1971. From 1971 to 1973 he was a Postdoctoral Research Associate at Rutgers University. In 1973, he joined NBS through a National Research Council Research Associateship. He joined the permanent staff at NBS as a research physicist in 1975, where his work has specialized in the study of electromechanical properties of superconductors, transport properties and critical current measurements, thin film interfaces in high temperature superconductors, and development of low resistivity contacts to high temperature superconductors. He has published over 150 articles and several book chapters on low-temperature transport properties of superconductors and normal metals, and received six patents for superconductor fabrication methods and devices. Currently, his research at NIST is focused on electromechanical measurements for the development of the "second generation" high temperature superconductors, the extension of the Strain Scaling Law from one to three dimensions, and the writing a textbook on cryogenic measurement techniques.

Prepared by J. W. Ekin.

Bibliography

[1] J. W. Ekin, Strain Effects in Superconducting Compounds, *Adv. Cryo. Eng.* **30**, 823-836 (1984).

[2] W. A. Pupp, W. W. Sattler, and E. J. Saur, Superconductivity of Thin Nb_3Sn Films Under Tensile Stress, *J. Low Temp. Phys.* **14**, 1-13 (1974).

[3] J. P. McEvoy, Effect of uniaxial stress on the superconducting transition temperature of monocrystalline Nb_3Sn, *Physica* **55**, 540-544 (1971).

[4] M. Pulver, Kritisches Verhalten von V_3Si und Nb_3Sn unter uniaxialem Zug im transversalen Magnetfeld, *Z. Phy.* **257**, 261-271 (1972).

[5] J. W. Ekin, F. R. Fickett, and A. F. Clark, Effect of stress on the critical current of niobium-titanium (NbTi) multifilamentary composite wire, *Adv. Cryo. Eng.* **22**, 449-452 (1977)

[6] J. W. Ekin, Effect of stress on the critical current of Nb_3Sn multifilamentary composite wire, *Appl. Phys. Lett.* **29**, 216-219 (1976).

[7] D. S. Easton and R. E. Schwall, Performance of multifilamentary Nb_3Sn under mechanical load, *Appl. Phys. Lett.* **29**, 319-321 (1976).

[8] I. L. McDougall, Stress induced degradation of critical currents in filamentary Nb_3Sn, in *Proceedings of the Sixth International Cryogenic Engineering Conference, Grenoble, 11-14 May 1976,* K. Mendelssohn (ed.), IPC Science and Technology Press, Guildford, England (1976) pp. 396-399.

[9] Thomas Luhman and M. Suenaga, The influence of thermally induced matrix stresses on the superconducting properties of Nb_3Sn wire conductors, *IEEE Trans. Magn.* **MAG-13**, 800-802 (1977).

[10] H. Hillmann, H. Kuckuck, H. Pfister, G. Rupp, E. Springer, M. Wilhelm, K. Wohlleben, and G. Ziegler, Properties of multifilamentary Nb_3Sn conductors, *IEEE Trans. Magn.* **MAG-13**, 792-795 (1977); G. Rupp, Improvement of the critical current of multifilamentary Nb_3Sn conductors under tensile stress, *IEEE Trans. Magn.* **MAG-13**, 1565-1567 (1977).

[11] G. Rupp, Stress induced normal-superconducting transition in multifilamentary Nb_3Sn conductors, *IEEE Trans. Magn.* **MAG-15**, 189-192 (1979).

[12] J. W. Ekin, Strain dependence of the critical current and critical field in multifilamentary Nb_3Sn composites, *IEEE Trans. Magn.* **MAG-15**, 197-200 (1979).

[13] J. W. Ekin, Strain scaling law for flux pinning in practical superconductors. Part 1: Basic relationship and application to Nb_3Sn conductors, *Cryogenics* **20**, 611-624 (1980).