ANALYSIS OF THE STRAIN DEPENDENCE OF THE CRITICAL TEMPERATURE OF Nb_3Sn

W.D. Markiewicz (NHMFL)

Introduction

The strain dependence of the critical properties of Nb_3Sn, including the critical temperature, the critical field and the critical current density, are well known, of technological importance, and are still the focus of a considerable research effort. Composite Nb_3Sn superconductors are the workhorse conductors that presently enable high field magnet applications, including fusion and high energy physics magnets. The strain dependence of Nb_3Sn is a significant design and fabrication constraint on magnets containing Nb_3Sn conductors, and further knowledge and predictability of the strain dependence is required for the engineering of these magnets. At present, the strain dependence of Nb_3Sn conductors is described by empirical equations applicable primarily to uniaxial applied strain. As a start to a comprehensive analysis capability for the strain dependence of all the critical properties, the present work provides a detailed analysis of the strain dependence of the critical temperature of Nb_3Sn. A simple physical model has been developed that relates the applied strain tensor to the characteristic features of the strain dependence of the critical temperature.

Analysis

The McMillan equation (1968) relates the critical temperature T_c to the physical properties of a strong coupled superconductor including the coupling constant and the characteristic frequency. A modern version of the McMillan equation used here is the equation of Kresin (1987) that applies to a wide range of values of the coupling constant and uses the normalized second moment of the spectral distribution function as the characteristic frequency. The key to developing a physical model containing the strain dependence is to explicitly include the lattice structure in the calculation of the coupling constant and characteristic frequency of strong superconductivity. The lattice structure is introduced through the calculation of phonon frequencies over all directions in the cubic crystal of Nb_3Sn. The pattern of phonon frequencies is reflected in the value of the critical temperature. An applied strain, or applied strain tensor, results in a change in the pattern of phonon frequencies in all directions in the crystal. The change in frequencies results in a change primarily of the coupling constant. The related change in the critical temperature is the strain dependence.

The strain dependence of the phonon frequencies and therefore of the critical temperature is contained in anharmonic terms of a proposed strain energy potential function for Nb_3Sn. The form of the strain energy potential is governed by the cubic symmetry of the lattice. The strain energy potential is expressed in terms of the scalar invariants of the strain tensor under the cubic symmetry group. It is therefore the cubic symmetry of Nb_3Sn that is reflected in the pattern of lattice vibration frequency change and in the form of the strain dependence of the critical temperature. Calculations done in this manner require determination of coefficients or amplitudes of the anharmonic terms of the strain energy potential. Presently these amplitudes are determined by a fit to the axial strain dependence data. In principle, these amplitudes may eventually be correlated with other aspects of anharmonic behavior in Nb_3Sn.

The resulting calculations exceed the empirical expressions in providing a fit over the full range of applied strain, and in correlating aspects of the strain dependence profile in a unified way. The calculations extend from the region of small intrinsic strain, where the empirical power law expression applies, to large compressive strain, where the empirical deviatoric strain description is used, and also to large tensile strain. The calculations reproduce the characteristic aspects of the strain profile, including the transition from a parabolic behavior at small strain to a linear profile at large strain, and even containing an inflection at large compressive and tensile strain. The way in which hydrostatic strain results in a depression of the critical temperature of composite conductors has been shown. The second invariant of the strain tensor is primarily responsible for the general parabolic dependence under uniaxial applied strain, while the third invariant appears to be responsible for the observed asymmetry. An approximate treatment has been developed that shows explicitly the way in which the strain invariants enter the calculation of the coupling constant and characteristic frequency.

References

[1] Markiewicz, W.D., Cryogenics 44, 767-782 (2004)
[2] Markiewicz, W.D., Cryogenics 44, 895-908 (2004)