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A MODEL FOR THE PREDICTION OF Nb_3Sn CRITICAL CURRENT AS A FUNCTION OF FIELD, TEMPERATURE, STRAIN, AND RADIATION DAMAGE

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Abstract

Conductors designed for fusion machines must operate at high fields, under large mechanical loads, and in a high neutron flux. Present designs favor the use of Nb_3Sn with force-cooling by supercritical helium to extract large nuclear and ac loss heat loads. Consequently, the magnet designer must have a good knowledge of the critical current of the superconductor as a function of field, strain, temperature, and radiation damage. Expanding on work by Hampshire, et al. and Ekin, combined with radiation damage studies of Nb_3Sn, we express the critical field (B_{c20}) as function of temperature, strain and damage energy (E_d). Similarly, the zero-field critical temperature (T_{c0}) is expressed as a function of strain and damage energy. The expressions for B_{c20} and T_{c0} are combined into a functional form that allows an accurate and consistent estimate of the critical current density at the operating conditions of fusion magnet conductors.

Introduction

Large magnet systems using forced-flow, supercritical-helium conductors are beneficial because of their compatibility with good winding rigidity, high-voltage insulation, and the predictable extraction of high heat loads. Forced flow conductors have therefore become essential elements of the design of magnets for fusion machines, such as the International Thermonuclear Experimental Reactor (ITER), where there is relatively high nuclear and a.c. heating.

Large forced-cooled magnets absorbing high heat loads cannot be operated isothermally. Therefore, the magnet designer must have a good knowledge of the performance of the superconductor as a function of temperature. This is especially true of ITER coils, many of which have their operational limits determined by temperature margin rather than current margin.

Additionally, superconductor performance in fusion magnets is further affected by the combined effects of strain (thermal and operating), and radiation damage. The sum of these effects makes it a difficult task to assess the usefulness of commercial Nb_3Sn superconductors in a reactor environment. Testing to validate superconductor performance under all reasonable combinations of operating conditions can prove to be prohibitively time consuming and expensive. This is especially true during early design stages where a number of superconducting wires are under consideration and the operating environment is subject to changes in response to changes in reactor and magnet design criteria.

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Here we present an empirical model that predicts the critical current density (J_c) of Nb_3Sn wires under the combined effects of temperature, strain, and radiation damage. The model, based on previous work of Hampshire et al.[1] and Ekin[2], predicts J_c with a reasonable degree of accuracy. More importantly the model can be used with a limited number of input parameters, eliminating the need for detailed characterization, particularly the difficult tasks of measuring critical current as a function of temperature and radiation damage.

Analysis

Field Dependence

Hampshire et al. performed a thorough analysis of Ta doped multifilamentary Nb_3Sn wires, measuring critical current density as a function of both field and temperature.[1] Their investigation confirmed a linear dependence of $I^{1/2} \times B^{1/4}$ vs B throughout the range of temperatures investigated, agreeing with the flux pinning model of Dew-Hughes.[3] Further analysis of their data shows that critical current density (J_c) can be described by the empirical relation

$$J_c(B,T) = C\, B^{1/2}\,(1-t^2)^2\, b^{-1/2}\,(1-b)^{1/2} \tag{1}$$

where $t = \dfrac{T}{T_{c0}}$

$b = \dfrac{B}{B_{c2}(T)}$

C = constant for a given wire

Furthermore they showed that

$$B_{c2}(T) = \kappa\,\gamma\,T_{c0}\,(1 - t^2) \tag{2}$$

where κ = Ginzburg-Landau parameter
γ = electronic specific heat coefficient

In their work, Hampshire et al. note that the Ginzburg-Landau parameter (κ) was temperature dependent, the normalized value ranging from 1.0 at T_{co} to approximately 1.5 at T = 0. For simplicity, we have taken a linear form for the temperature dependence of κ, specifically

$$\frac{\kappa(T)}{\kappa(T_{c0})} = \left[1 - \frac{1}{3}\,(T/T_{c0})\right] \tag{3}$$

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We claim no physical significance for this expression, but prefer it as the simplest form providing an acceptable fit to the temperature dependence data for κ within the experimental error shown.

If one combines this expression for the Ginzburg-Landau parameter with equation 2, the temperature dependent upper critical field can be expressed as

$$B_{c2}(T) = B_{c20}(1 - t^2)\left[1 - \frac{1}{3}t\right] \quad (4)$$

Strain Dependence

From this point it is relatively straight forward to incorporate the expressions derived by Ekin for the strain dependence of the upper critical field and critical temperature. Ekin gives the following expression for the strain and temperature dependence of B_{c20} and T_{c0}.

$$B_{c20}(\varepsilon) = B_{c20m}\left(1 - a\,|\varepsilon|^u\right) \quad (5)$$

$$T_{c0}(\varepsilon) = T_{c0m}\left(1 - a|\varepsilon|^u\right)^{1/w} \quad (6)$$

where B_{c20m} and T_{c0m} are the values of B_{c20} and T_{c0} at zero intrinsic strain.

and using

$a \approx 900$ for $\varepsilon < 0$, $a \approx 1250$ for $\varepsilon > 0$
$u = 1.7$
$w = 3$

Ekin obtained an excellent fit to available data.[2]

Combining equations 1, 4, 5 and 6 we obtain the field, temperature, and strain dependence of J_c

$$J_c(B,T,\varepsilon) = C\left(B_{c2}(T,\varepsilon)\right)^{-1/2}\left(1-t^2\right)^2 b^{-1/2}(1-b)^2 \quad (7)$$

where

$$B_{c2}(T,\varepsilon) = B_{c20}(\varepsilon)\left(1 - t^2\right)\left[1 - \frac{1}{3}t\right] \quad (8)$$

and now

$t = T/T_{c0}(\varepsilon)$

$b = B/B_{c2}(T,\varepsilon)$

C = pinning/geometry constant accounting for the amount of Nb_3Sn in the non-Cu fraction and the effectiveness of pinning sites.

Radiation Damage Dependence

Similarly, an accounting for radiation damage dependence must also include radiation induced changes in T_{c0} and B_{c20}. In addition, dissimilar swelling of Nb_3Sn and the surrounding bronze and copper matrix will change the strain state of the Nb_3Sn requiring a further accounting for radiation induced strain. Ideally these effects should express B_{c20} as a function of the electronic specific heat (γ), normal state resistivity (ρ), with separate parameters for strain and disordering changes in T_c.

Hahn, et al. have studied the effects of radiation damage on T_c in a number of multifilamentary wires.[4] They have found that T_c as a function of damage energy $\left(T_{c0}(E_d)\right)$ can be expressed as

$$T_{c0}(E_d) = T_{c0}(0)\,e^{-E_d/4} \quad (9)$$

where E_d is in eV/atom (note that for 14 MeV neutrons 1 eV/atom $\approx 4 \times 10^{22}$ n/m^2)

Reliable measurements of the electronic specific heat of Nb_3Sn vs radiation damage and swelling strain (ε_d) on T_c have been made by Nölscher and Saemann-Ischenko.[5] For the case where the change in T_c small (less than 6-8 K) their results can be rewritten in terms of damage energy giving

$$\gamma(E_d) = \gamma(0)\,e^{-\frac{3}{8}E_d} \quad (10)$$

$$\varepsilon(E_d) = \frac{\Delta a}{a}(E_d) = 5.0 \times 10^{-4}\,\Delta T_c(E_d) \quad (11)$$

where a = Nb_3Sn lattice parameter

The total strain in the wire is the sum of the radiation induced strain $\left(\varepsilon(E_d)\right)$ and mechanical strains due to thermal precompression and operating forces (ε_m). Thus Ekin's equations can be rewritten as

$$B_{c20\varepsilon}(E_d) = B_{c20m}\left(1 - a\,|\varepsilon_m + \varepsilon(E_d)|^u\right) \quad (12)$$

$$T_{c0\varepsilon}(E_d) = T_{c0m}\left(1 - a|\varepsilon_m + \varepsilon(E_d)|^u\right)^{1/w}\left(1 - T_{c0}(E_d)\right) \quad (13)$$

Normal state resistivity as a function of neutron dose in Nb_3Sn had been measured by Brown, et al.[6] A fit to their data in terms of damage energy gives

$$\rho = \rho_o + 800\,E_d \quad (14)$$

where ρ is in n$\Omega \cdot$ m

Combining equations 10 and 14 we have an expression for the change in upper critical field due to radiation damage

$$\frac{B_{c20m}(E_d)}{B_{c20m}(0)} = \frac{\rho_o + 800\,E_d}{\rho_o}\,e^{-\frac{5}{8}E_d} \quad (15)$$

We can now rewrite equation 7 combining all the effects of radiation damage which gives

$$J_c(B,T,\varepsilon,E_d) = C\left(B_{c2}(T,\varepsilon,E_d)\right)^{-1/2}\left(1 - t^2\right)^2 b^{-1/2}(1-b)^2 \quad (16)$$

where we now have

$$B_{c2}(T,\varepsilon,E_d) = B_{c20}(\varepsilon,E_d)\left(1 - t^2\right)\left(1 - \frac{1}{3}(t)\right)\left(1 - B_{c20m}(E_d)\right) \quad (17)$$

$b = B/B_{c2}(T,\varepsilon,E_d)$
$t = T/T_{c0}(\varepsilon,E_d)$

Calculations

Field and Temperature Effects

The empirical fit we have developed appears self consistent and we have compared calculated results with reliable data reported in the literature. In Figure 1 we show data obtained by Suenaga, et al. for the critical current density as a function of field and temperature for Nb_3Sn together with the results of the model presented here.[7] In order to obtain this fit we assumed a precompression of - 0.3 % a reasonable assumption for multifilamentary Nb_3Sn. Then only 3 input parameters, C, B_{c20m}, and T_{c0m}, are varied to obtain the best fit to the experimental data at 4.2 K. The best fit is obtained when B_{c20m} = 29 T, T_{c0m} = 18.3 K, and C = 10,700 AT mm^{-2}.

These parameters are held constant for calculation of J_c vs B at temperatures other than 4.2 K. There is excellent agreement between the sub 4.2 K experimental data and prediction. Furthermore, $B_{c2}(T,\varepsilon)$ obtained by Kramer plots of Suenaga's data at 4.2 K is 24.1 T, identical to that predicted using this model.

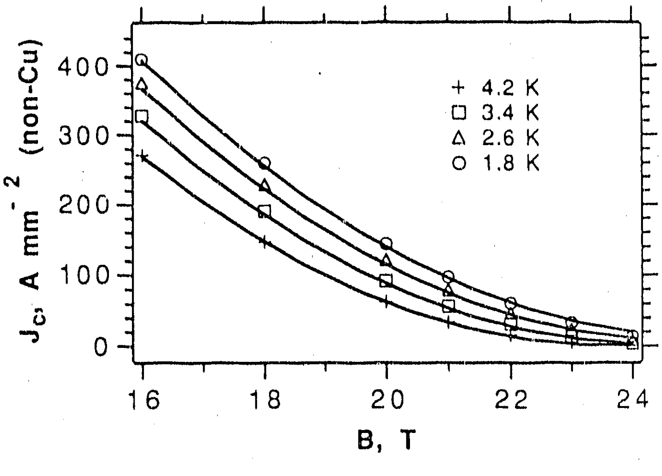

Figure 1. Comparison of calculated values of J_c vs actual data obtained by Suenaga, et al.

Figure 2 shows a plot of data obtained by Spencer, et al. for a bronze process Nb_3Sn wire.[8] This data was obtained at low fields and at temperatures above 4.2 K. The best fit to the 4.5 K data was obtained using B_{c20m} = 25.3 T, T_{c0m} = 18.69 K, and C = 6400 AT mm^{-2}. Holding these values constant, J_c at the higher temperatures was calculated. The fit of experimental and calculated data is reasonably good, however, there is a divergence at combinations of high temperatures and very low fields.

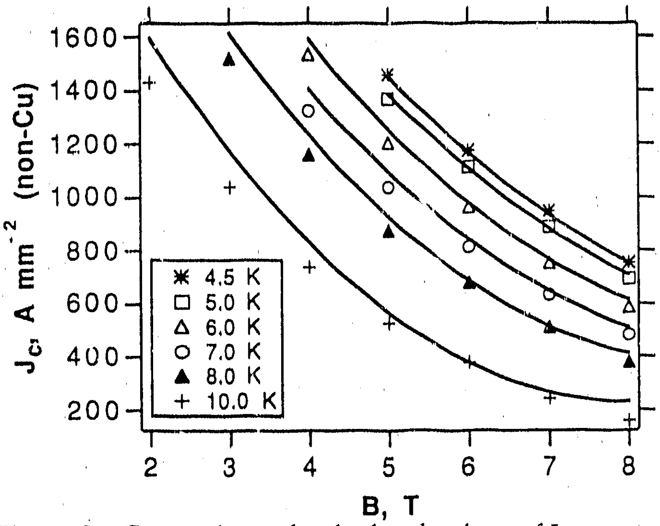

Figure 2. Comparison of calculated values of J_c vs actual data obtained by Spencer et al.

Strain Effects

The authors have investigated the strain and field dependence of critical current density in Ti-alloyed multifilamentary Nb_3Sn wires. Figures 3 and 4 show the critical current as a function of strain and field respectively. For the purposes of calculation, B_{c20m}, T_{c0m}, and C were set to 27.5 T, 18.3 K, and 17,500 AT mm^{-2}, which gave the best fit to the strain dependence data. These values were held constant for calculation of J_c vs B. The experimental fit to calculated data is good at high fields but tends to diverge at lower fields.

Radiation Damage Effects

Comparison of experimental and calculated data is in progress and will not be reported here.

Discussion

The model presented effectively combines Hampshire's field and temperature dependence of J_c with

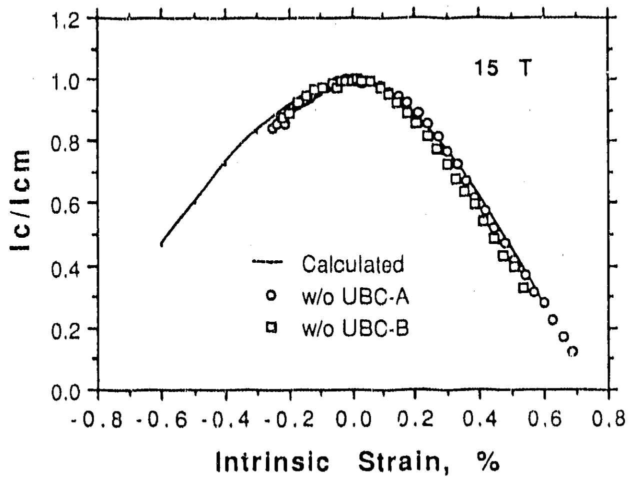

Figure 3. Critical current as a function of longitudinal strain for wires without under-barrier copper. Data is shown for two specimens (A&B). The solid line is a fit to calculated values of the strain dependence.

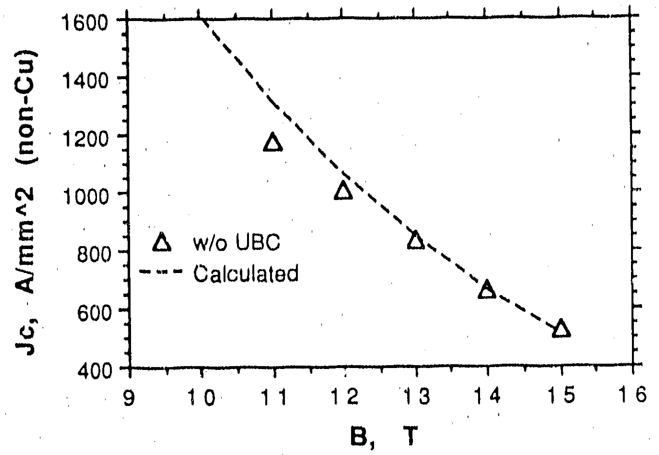

Figure 4. Jc as a function of B for internal-Sn Nb_3Sn wires without under-barrier copper.

Ekin's strain dependence in a simple functional formula. The critical current density as a function of field, temperature and longitudinal strain can be predicted with a reasonable degree of accuracy.

Radiation Damage Effects

Comparison of experimental and calculated data is in progress and will not be reported here.

Discussion

The model presented effectively combines Hampshire's field and temperature dependence of J_c with Ekin's strain dependence in a simple functional formula. The critical current density as a function of field, temperature and longitudinal strain can be predicted with a reasonable degree of accuracy.

The strength of this model is in its ability to predict performance based on a limited number of input parameters. Essentially only two tests need to be performed, measurement of strain dependence, and critical current at atleast 2 fields. Assumptions of B_{c20m} and T_{c0m} can be made by fitting to the J_c vs ε data. After B_{c20m} and T_{c0m} are determined, C can then be adjusted to fit the field dependence of J_c. Critical current density as a function of all parameters (ε, B, T), taken either singly or in combination, can then be predicted with a fair measure of accuracy.

The ability of the model to handle radiation effects has yet to be tested. However, the model is self consistent in the manner with which radiation damage is accounted for and reasonable predictions are expected.

Conclusions

An functional form of an empirical model for prediction of J_c in multifilamentary Nb_3Sn is presented. This model combines an empirical fit of the field and temperature dependence, as determined by Hampshire, et al., with the longitudinal strain dependence formulated by Ekin. Additional terms for radiation damage dependence are proposed based on an accounting for changes in T_{c0}, swelling induced strain, and increases in normal state resistivity. The predicted strain, temperature, and field dependence of J_c is found to agree reasonably well with experimental data.

Acknowledgments

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