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Y. Zhai

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Numerical Stress Analysis during Cooldown and Compressive Loading in an Imperfect Nb_3Sn Wire

Luc d’Hauthuille[1] and Yuhu Zhai[2]

[1]Department of Physics, University of California Santa Cruz, Santa Cruz, CA, USA
[2]P.O. Box 451 Princeton Plasma Physics Lab, Princeton, NJ, USA *Phone: 609-243-3056, Email: yzhai@pppl.gov

TOFE Abstract # 17996

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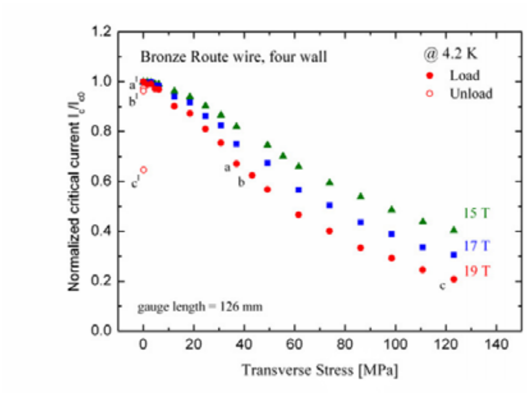
Abstract - **High field superconductors are critical to the success of next step magnetic fusion confinement devices such as ITER and DEMO. The low-temperature superconducting material that is currently favored for these applications, Nb3Sn, is susceptible to performance due to its brittleness and high strain-sensitivity. Under extreme loads, an irreversible degradation in the maximum critical current density has been shown to occur and believed to be strongly influenced by two factors: plasticity and cracked filaments. Cracks in filaments are induced when sufficiently high stress concentrations occur in the wire. In this paper, we explore using finite element analysis the impact that voids have on the stress distributions and peak stresses under two loading conditions: transverse compressive loading in a 2D model, and a full cool down phase in a 3D model.**

I. INTRODUCTION

Large superconducting coils form a central part of the International Thermonuclear Experimental Reactor (ITER) due to their ability to generate extreme magnetic fields. In the three sets of coils that make up the magnet system in ITER, the two that generate the largest magnetic fields and are paramount in confinement are the Toroidal Field (TF) coils and the Solenoid Coils. The low-temperature superconductor that was chosen for these coils is Nb_3Sn due to its high critical current and long history of success.

The primary issue with Nb_3Sn is that its performance is highly dependent on mechanical loading. Mechanical loads affect the performance in two ways: distortion of the lattice, which affects superconducting parameters, and cracking of filaments which irreversibly affects the wire. Mechanical loads occur due to the Lorentz Force. Reversible degradation in performance through a decrease in critical current density (J_c) has been shown to occur when the a wire is under axial or transverse stress.[1-7] After unloading, the wire returns to its original state and regains its maximal critical current density. An irreversible degradation in performance occurs when a Nb_3Sn wire is subject to a stress (or strain) that is higher than the irreversible limit,[8] after unloading there is a permanent decrease in the maximal critical current density (Figure 1). During the fabrication of a bronze-route Nb_3Sn wire, heat treatment (HT) at 900-1000 K is necessary for the Nb filaments to react with the tin in the bronze matrix and become Nb_3Sn. During this reaction, the displacement of the tin results in the formation of regions of void throughout the wire (Figure 2). The voids are visibly of various shapes and sizes but all cause concentrations in stress that would not appear otherwise. In addition, when the wire is cooled down from heat treatment to room temperature and later working temperature (4 K), pre-strain occurs in the wire which is also thought to be important in determining irreversible limit.



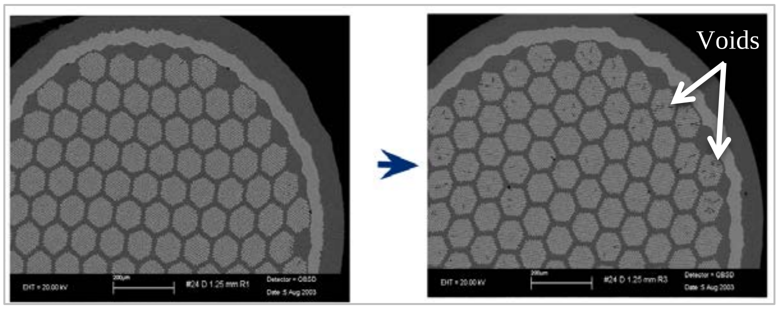


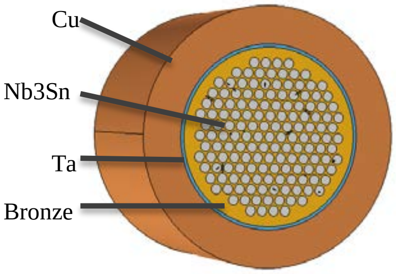
Figure 1: Normalized J_c vs Transverse stress

Figure 2: Void formation occuring (Pre-HT to Post-HT)

Collaboration between the University of Geneva and Princeton Plasma Physics Lab has been established to study how voids correlate with the irreversible strain limit which leads to permanent degradation. Based on tomography done at the University of Geneva which has yielded statistical data on void sizes and shapes,[9] we explore the effect that various voids have on the stress distributions and peak stresses in a bronze-route Nb_3Sn wire under two loading conditions using finite element models. The first model looks at transverse compressive loading with a 2D geometry where the plane strain approximation is used and the wire is at its working temperature, 4 K, with an applied load that has been shown to cause irreversible degradation in a similar experiment.[10] The second is a 3D model with the same shaped voids present (but extruded to fit the model) and the cool down process is applied from 923 K to 4 K to analyze the thermal pre-stress in the wire.

II. METHODOLOGY

The finite element models were created in COMSOL and based off a cross-section of Bruker bronze-route Nb_3Sn strand, which consists of four materials: an outside layer of Copper, a thin shielding of Tantalum, a Bronze matrix and Nb_3Sn bundles of filaments organized in hexagons throughout the matrix (Figure 3). The hexagonal bundles of filaments were simplified to circles consisting purely of Nb_3Sn, as opposed to true bundles containing many filaments, for the sake of convergence. Previous studies[2] have shown that there is little difference in the stress distribution of fully modeled bundles and these homogenized bundles. While the 3D model's geometry was simply an extrusion of the 2D geometry, the material properties used differed between the two loading conditions. Additionally, a fine adaptive mesh was used in both models as seen in Figure 4.



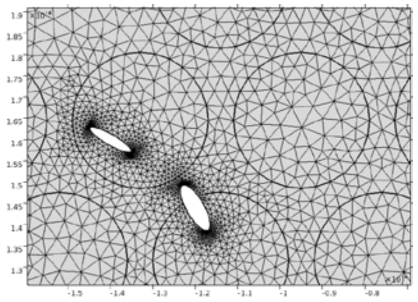


Figure 3: Bronze-route Nb_3Sn strand geometry. Different colors correspond to different materials.

Figure 4: The adaptive mesh in the 2D model near voids

In the 2D model where the compressive load was applied, the materials were said to all be purely elastic and properties calculated for the materials at 4 K. In the 3D model, a bilinear elastic model was used for all materials (besides Nb_3Sn) with temperature-varying Young's modulus, tangent modulus, yield stress and coefficient of thermal expansion. Figure 5 shows the bilinear stress-strain curves for copper at 3 temperatures and Figure 6 shows the thermal contraction of the different materials expected over the cool down. All material properties were based on Mitchell's work,[1] and Calzolaio's et al.'s paper.[10]

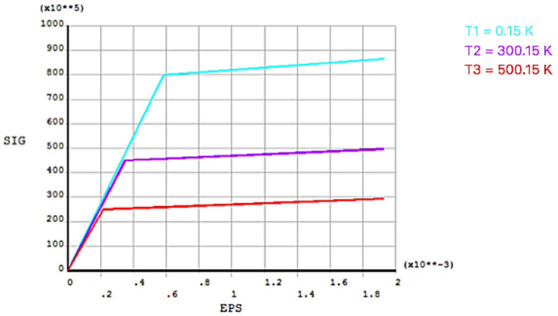


Figure 5: Bilinear stress-strain model for Copper

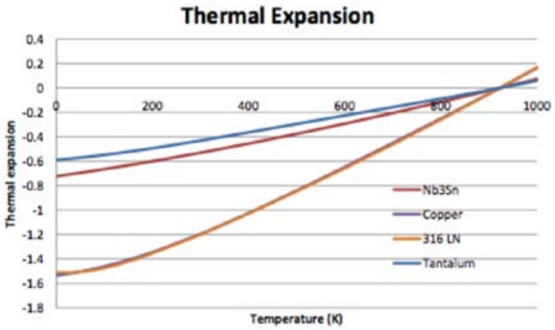


Figure 6: Integrated thermal expansion (%) of materials

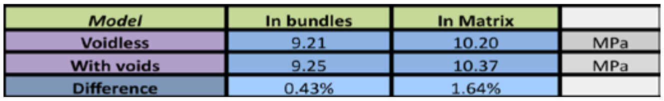
The plane strain approximation was used in the 2D model, and the transverse compressive load was applied based on the 4-wall method frequently used for strand testing, with a surrounding square epoxy resin and a uniform force load applied to the top boundary. The boundary at the bottom of the epoxy was held fixed and the left and right walls were free to move. Since the irreversible limit for a similar wire (although a powder-in-tube one) was found to occur at 17 kN,[10] this was the applied force chosen for the top boundary. In the 3D model, the 2-step cool down which occurs to bring a Nb_3Sn wire from heat treatment temperature to its working temperature was simplified to a 1-step cool down from 923 K to 4 K. One end of the wire was held fixed and the cool down was simulated by placing the wire in an "air bath", where the domains in the wire all began at 923 K and the ambient temperature was set to 4 K with a heat transfer coefficient of 500 W/(m^2•K).

Voids were implemented in an ad hoc fashion and to the scale of the model, with sizes and shapes based on the statistical void data provided by the University of Geneva. Since the model was detailed only to the bundle level, inter-filamentary voids were not implemented as the focus was on voids that were comparable to bundles in size. Three distinct types were studied: voids fully inside bundles, partially inside bundles and voids purely in the matrix between bundles. 15 voids were implemented in total, the largest of which was 99.15μm^2 in area and the smallest

6.85μm^2, with an average size of 45.68 μm^2. These were manually generated in COMSOL and took the shapes of high eccentricity ellipses, circles and an amalgamation of these. Their boundaries were free.

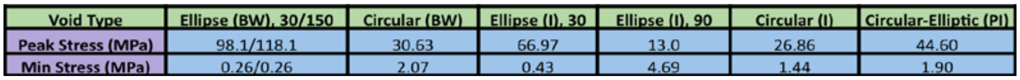
III. RESULTS & FINDINGS

A. 2D Model



Model	In bundles	In Matrix	
Voidless	9.21	10.20	MPa
With voids	9.25	10.37	MPa
Difference	0.43%	1.64%	

TABLE I: Comparison of average stress across all bundles and the whole matrix



Void Type	Ellipse (BW), 30/150	Circular (BW)	Ellipse (I), 30	Ellipse (I), 90	Circular (I)	Circular-Elliptic (PI)
Peak Stress (MPa)	98.1/118.1	30.63	66.97	13.0	26.86	44.60
Min Stress (MPa)	0.26/0.26	2.07	0.43	4.69	1.44	1.90

TABLE II: Stress concentration by void type and orientation

First, a global comparison was done of the average stress in the Nb_3Sn bundles and bronze matrix of a model with and without voids under a transverse compressive load. The results reported in Table I show that there is a small increase of 0.43% in the average stress in bundles and 1.64% in the average stress in the matrix when the voids were included. Figure 7 also shows visually that even the largest simulated void has only a local effect on the stress distribution (i.e. it only affects the stress in the nearest bundles). On the other hand, locally large stress perturbations occur due to the voids. The effect of these perturbations is largely dependent on the void's size, shape and orientation. Table II shows a summary of the peak stress and minimum stress found to occur near the void types investigated. These local stress concentrations may initiate potential cracks because the irreversible stress limit for the bronze-route wire is around 120-160 MPa. The resultant cracks have been shown to reduce the mechanical performance of the wire, as in a permanent reduction of the wires irreversible strain limit.

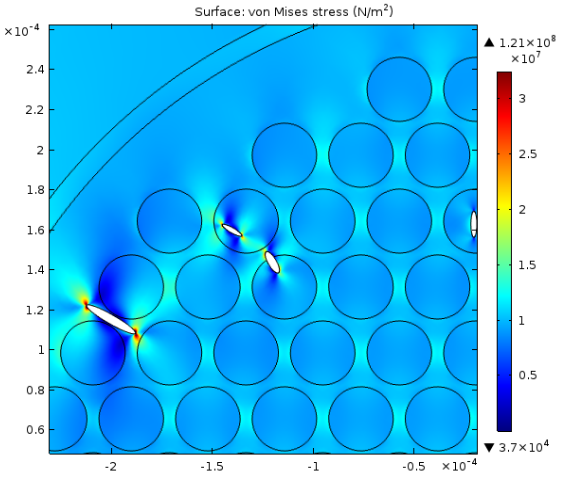


Figure 7: Stress perturbations near elliptical voids

B. 3D Model

A successful cooldown from the heat treatment temperature of 923 K to 4 K was performed with the 3D bi-linear temperature dependent model. The thermal strain observed post-cooldown is consistent with the theoretical expectations,[1] as seen in Figure 8. The thermal stress was evaluated by looking at the Von Mises stress seen in Figure 9. The average Von Mises stress across the bronze matrix was 1.89 GPa, while across the tip of the voids it was found to be around 3.95 GPa. Voids had little to no effect on the thermal stress, those with a maximum effect only increased the stress in a small area by a factor of 1.7. Additionally, the correlation between the type of void and the resulting stress perturbation was much less clear than in mechanical loading. Overall, there is significant built-in stress from the cool down phase, so we expect it to have an important effect on future mechanical loading studies.

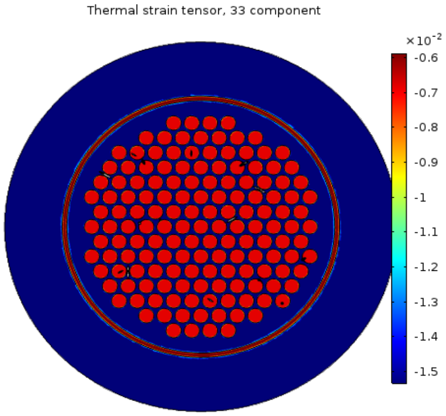


Figure 8: Thermal Strain (33 component)

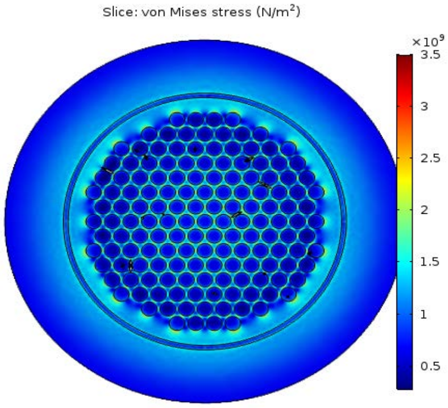


Figure 9: Resultant Von Mises Stress

IV. CONCLUSIONS & FUTURE WORK

In this paper we explored two finite element models of bronze-route Nb_3Sn wires under two different loading conditions. In the 2D Model, the plane strain approximation was used and a compressive load of 17 kN was applied to the wire using a 4-wall scheme and through a surrounding epoxy mold. When several voids were included, the global stress distribution did not change significantly, with less than a 1% increase in the average stress throughout the bundles and matrix. Locally, large stress perturbations with peak stresses upwards of a factor of 11 were shown to occur near voids, and where the magnitude of the perturbation had a significant dependence on size, shape and orientation. These results are consistent with previous work on a model to the filament detail. Voids were generated manually and based on inspection of X-ray diffraction images from the University of Geneva, which presented an important limitation in the number of voids that could be generated as well as the complexity of their geometry.

A full simulation of the cooldown was completed, which was a significant advancement from previous work where mesh inversion issues caused the simulation to end prematurely. The thermal strain seen was consistent with theoretical predictions. Then, the thermal Von Mises stress was evaluated in a cross-section of the wire and the contributions of simplified voids (extrusions of 2D voids) were studied. The impact on the stress distribution due to these voids was minimal, with some having practically no effect and the largest effect being less than a factor of two increase in stress in a very small area. Overall, the thermal pre-stress from the cool down was determined, which can now be incorporated in the initial conditions of future studies at 4 K to perform more realistic simulations of loading conditions in the wire.

In future work two trajectories will be pursued. The first is to use these built-in stress results at 4 K as the initial state for future FEA models to more accurately model the stress under different mechanical loading conditions. The stationary study of transverse compressive loading by the 4-wall method will be revisited and a comparison between the results with and without pre-stress will be performed. Additionally, we aim to study the effect of axial tension on stress concentrations in the wire, which could not be done accurately without the thermal pre-strain. The results of these studies can then be used in conjunction with fracture mechanics to predict the loading conditions that cause filament fracture. The second trajectory will consist of better and more accurately modeling voids. Using COMSOL's Java API, code will be written in Java to automate the process of generating voids, eliminating the time-consuming task of manually generating them. A Monte Carlo algorithm will be developed based on statistical void data taken at the University of Geneva to populate 2D and 3D models with arbitrary amounts of voids whose size, shape and orientation distribution are based on voids observed in University of Geneva's tomography experiments.

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