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A multilevel homogenised model for superconducting strand thermomechanics

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Abstract

In the present concept of ITER fusion reactor the toroidal field and the central solenoid coils are made of Nb_3Sn based strands with the cable-in-conduit-conductor (CICC) technology. It is well known that the critical parameters of the Nb_3Sn strand material are strain sensitive; experimental investigations on short samples of basic strands and subsize CICC cables already demonstrated significant effects of residual strain on the critical parameters. In this paper a method is proposed to analyse in detail the thermal strain induced by the cool down from the strand reaction temperature to the coil working conditions. The superconducting strand can be regarded as a very good example of a hierarchical structure, since there is a clear distinction between the micro-scale of the Nb_3Sn filaments, the meso-scale of the SC filament groups and the macro-scale of the strand, where it can be regarded as homogeneous. A constitutive relation for the homogenised micro- and meso-components is deduced from the knowledge of the respective internal structures, starting from an accurate description of the single representative cells. This two-scales homogenisation technique is associated with an efficient finite element procedure for computing effective material coefficients to be used with standard orthotropic 3D elements in structural codes. Finally the finite elements routines developed for the unsmearing process provide the real stress and strain values over each single material, which are essential to catch the local features needed for engineering design.

Keywords: Multiscale homogenisation; Hierarchical composite; Thermal strain; Multifilament superconducting strand; Finite element technique

1. Introduction

This paper is part of a long lasting research effort to tackle the electro-mechanical and thermo-mechanical analysis of superconducting coils for ITER. These coils are rather complicated heterogeneous structures, where up to five scales can be observed: from the single filament (2–5 μm) to the conductor and up to e.g. a full D-shaped toroidal field coil, which may have a height of 13 m. With the actual computer power at disposition, multiscale analysis techniques are the most appropriate means to take into account at higher level the information contained at lower scales.

First we have addressed the global analysis of the coils under electromagnetic body forces, starting from the single conductors as local structure. In this instance the behaviour could be assumed as linear and asymptotic theory of homogenisation has been used [1–3]. An alternative model for the D-shaped coil, as a beam of unidirectional composites has also been developed [4–6].

Then we have addressed the behaviour of the single conductor, which is strongly non-linear, presenting in the stress–strain (load–displacement) diagrams micro-plasticity and hysteresis under cyclic loading.

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In that case some experimental data were available [7] and therefore two approaches involving artificial neural networks have been developed [8,9].

Now we are at the lower end of the scales, where we try to obtain the material properties of the strand and the triplets of strands starting from the knowledge of the behaviour of the filaments and the matrix.

The thermo-mechanical behaviour of these materials is piece-wise non-linear (not so strongly non-linear as the cable) and therefore we make use again of the theory of homogenisation, adapted for such a case. In this article we tackle the problem of the strand, where a three-level homogenisation strategy is necessary (filament—group of filaments—strand).

In a subsequent paper we will deal with the modelling of the triplets of strands, where the tool developed in [4–6] could be successfully applied.

We now first describe the strands and the problems connected with them, then we propose the multiscale asymptotic homogenisation method that will be used and finally we show as an example the application of this method to the analysis of an ITER strand.

Recent experimental tests, performed within the Model Coil projects frame at the test sites in Naka (Japan) and Karlsruhe (Germany), demonstrated that present ITER design criteria are satisfactory and the coils operate quite stably. The main part of ITER coils, precisely the toroidal field (TF) coils and the central solenoid (CS), is likely to be manufactured with Nb_3Sn based strands, with the cable-in-conduit-conductor (CICC) technology.

Within a strand the Nb_3Sn superconducting alloy is arranged in form of very fine filaments (2–5 μm diameter) which are collected into groups, twisted together and generally embedded in a bronze matrix (Fig. 1). A very low resistivity material, typically oxygen free high conductivity (OFHC) copper, usually surrounds the SC filament groups (Fig. 2).

The subdivision into fine filaments is required to eliminate instabilities in the superconductor, while the filament twisting is introduced to reduce inter-filament coupling when the wire is subjected to time varying fields. The low resistivity matrix is used as a current shunt in the case of a transition of the filaments to the normal resistive state, thereby limiting power dissipation and conductor heating since the resistivity of superconductors in the normal state is usually quite high.

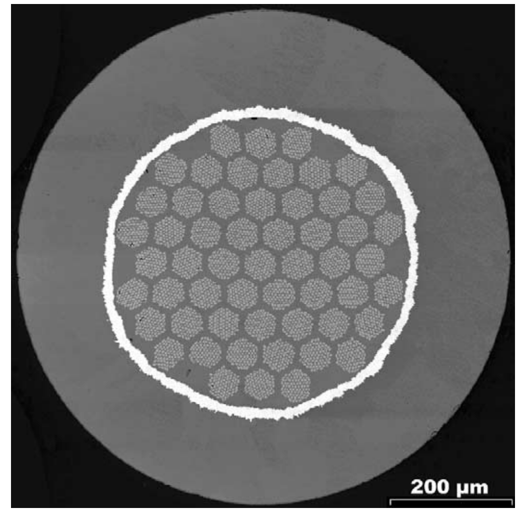

Fig. 2. EAS (European Advanced Superconductors former Vacuumschmelze (VAC)) strand: bronze route type with filaments collected in 55 groups of 85 filaments embedded in a bronze matrix [13]. A tantalum thick barrier divides the bronze from the outside OFHC copper matrix.

Because of its brittleness, Nb_3Sn cannot be extruded and drawn, as it is done for NbTi superconducting alloy. The alternative is to proceed first by assembling a billet including uncompounded precursors of Nb_3Sn, secondly processing the billet until the desired wire size is achieved, finally cabling and heat treating the final cable (or coil) to form Nb_3Sn compound. At least four processes are used industrially to manufacture Nb_3Sn wires (bronze route process, internal tin process, modified jelly roll process, powder in tube process) and they all require a high temperature heat treatment on the final size cable. The typical heat treatment consists of hundreds of hours around 650 °C in a vacuum or in inert gas to prevent Cu oxidation.

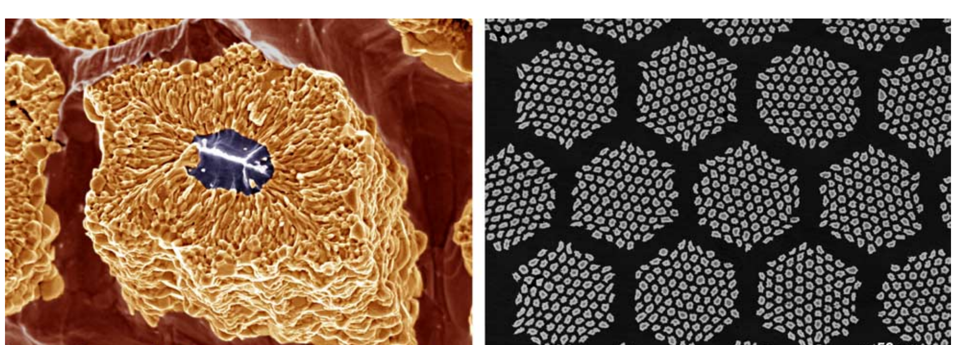

Fig. 1. A single Nb_3Sn filament (left) and a Nb_3Sn filaments group (right); the respective scales are also evidenced [13].