Recent Improvements of Residual Stress Analysis of Composite Superconductor Cables for Fusion Magnet Windings

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Abstract

After completion of the design, manufacture and acceptance testing of the EURATOM LCT-coil a sizeable effort at KFK is now focused on studies concerning A-15 type superconductor development and preliminary designs for the NET toroidal (TF) and poloidal (PF) field coils.

This extended summary is an introduction to the conference talk and a following more comprehensive paper which gives a formalized description of partly hollow cross sections of presently envisaged superconductors. It discusses the analysis of plastic bending by "homogenized" and heterogeneous conductor cross section models. The extended paper presents typical results on rope-wrapping, conductor bending and winding, cable lift-off and layering, and springback.

1. Introduction

After the completion of the design and approval of the Euro-LCT-coil /1,2,3/ the focus of the development effort at KFK in the field of A-15 type superconductor development /4/ is now on the preliminary designs for the NET toroidal /5/ and poloidal /6/ field coils. For both coil types it seems desirable to dispense with massive metal casing structures in order to avoid difficulties connected with limitations of available space, acceptable eddy current losses, etc. Consequently more emphasis will have to be placed on the internal reinforcement provided by the new concepts of superconductor cables in the near future. Improvements beyond the lessons learned from the LCT-coil development must indicate with greater precision than for existing large coil technology (like NbTi)

- possible compromises between easy handling (mechanical flexibility), sufficient cooling (relatively complex cable cross section) and required reinforcement (stiffness of winding cross sections and central support vault) of the superconductor cable, and
- the self-equilibrating stresses within the coil immediately after the completion of the manufacture.

Some arguments pertaining to particular TF and PF coil situations (heating and cooling, support forces, loadings under operational and fault conditions in the reactor environment) were given in /7,8/. They explain the complexities of some different composite cross sections recently proposed for these new (to be developed) superconductor cables (see figures below).

Hitherto the bending of composite superconductor cables was described by a simplified elastica/plastica model with an assumed solid rectangular cross section /9/. This simplification should be abandoned when the margins to failure and the allowable prestress levels for cycling elastoplastic strains within such complex cross sections containing A-15 type superconductors are to be quantified. Plastic forming occurs in the rope-wrapping process applied to the superconducting strands during cable production, in the winding procedure of planar and nonplanar coils, in the complicated shapes of the conductor near the power supplies, in the crossing-over of a cable between adjacent pancakes, etc. Usually the underlying bending may be plainly planar, sequentially planar, or truly biplanar. Elastic unloading can occur in particular regions of a wire, cable or winding pack under a change of the spatial load distribution and/or a proportional reduction of the load level.

This extended summary restricts itself to the presentation of an outline of a few fundamental mechanical problems of residual stress analysis for composite superconductors as well as to a cursory description of some modelling aspects. It tries to explain the line of reasoning behind the numerical analyses in the form of a topical survey. As intended by the organizers of this conference division (N) selected details and results will be given in the conference talk and will be later published in a more comprehensive text.

This paper gives a formalized description of partly hollow cross sections which covers the common features of our proposed cables. It discusses the analysis of plastic bending by "homogenized" and heterogeneous conductor cross section models. Plastic forming and elastic unloading effects during rope-wrapping (with a look on Roebel wrapping) and cable bending (planar or not) determine the residual strains and ensuing stresses during coil manufacture /10/ and eventual operational accumulation of fatigue damage. It is shown that the composition of the cross section "shapes" the moment/curvature relationship M(k) of the cable which for its part sensibly influences the numerical method used to find the residual strain in the outer fiber after springback. The connection between formal types of M(k)-curves (like elastic-ideal plastic, bilinear to "grasp" hardening) and the mathematical structure of the corresponding equations and solution procedures is explained. Finally the comprehensive paper presents typical results which pertain to applications like rope-making, conductor bending experiments, winding, lift-off and layering of the cable with some emphasis on repeated plastic forming and elastic springback.

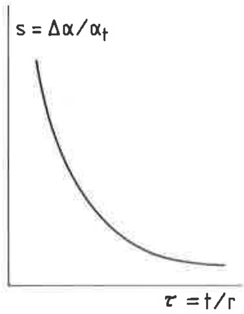
2. Outline of Mechanical Problems of Residual Stress Analysis for Composite Superconductors

In the following we present some of the illustrations of the talk together with some very short explanations. Figures 1 and 2 give results on the plastic bending and springback of the existing LCT-NbTi superconductor. Fig. 3 compares this conductor with some recently proposed concepts for future A15-superconductors. Finally, Fig. 4 gives some actual mechanical research topics in the development of future A15 superconductors.

The critical mechanical problems yet identified for the layout of the composite cables and their comparative evaluation are

- mechanical resistance against quench pressure
- ease of wrapping (plastic straining of the subcables) versus
  ease of forming during winding (plastic bending of the cable, compression and distorsion of subcables, subchannel and wrapper, eventual friction effects, etc.)

RELEVANCE OF RESIDUAL STRESSES FOR THE MANUFACTURE OF LARGE COILS

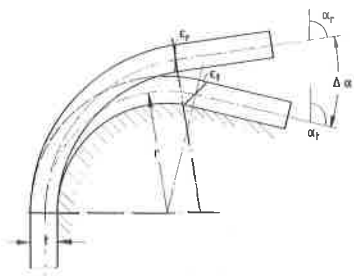


springback ratio

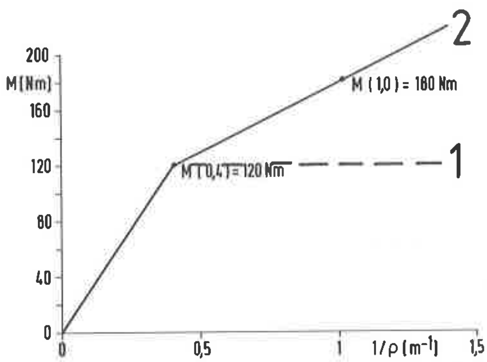
The residual stresses

- **are determined by the metal forming process parameters during the winding procedure**
- **determine the initial stress and strain conditions before operational and/or fault loadings are applied**

RESIDUAL STRESS ANALYSIS OF A CIRCULAR BEND



- **planar bending**
- **nonplaner bending**
- **repeated loading**



1: s(t/r) is explicit

2: f(s,t/r) is implicit

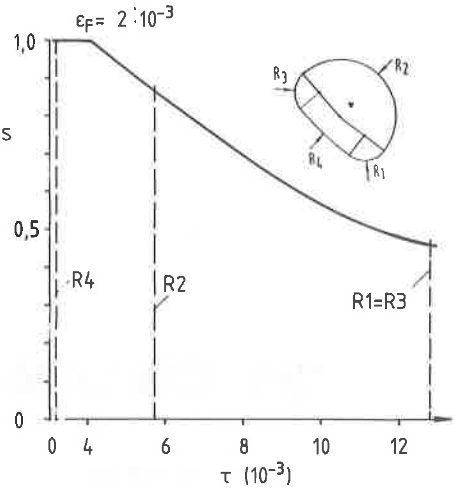
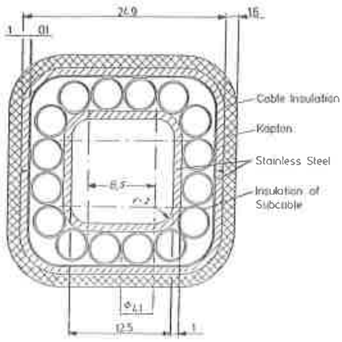


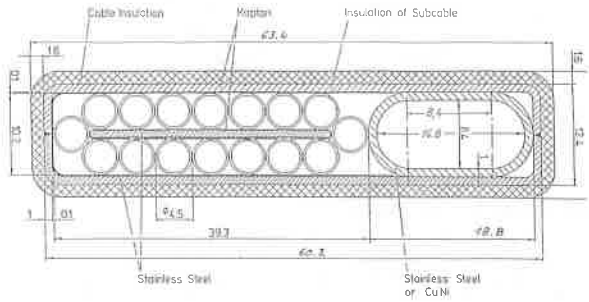
Fig. 2: Springback ratio of the

LCT-superconductor

Fig.1:
Bending moment/curvature-relationship for the superconductor cable (experimental data: EURATOM-LCT-coil)

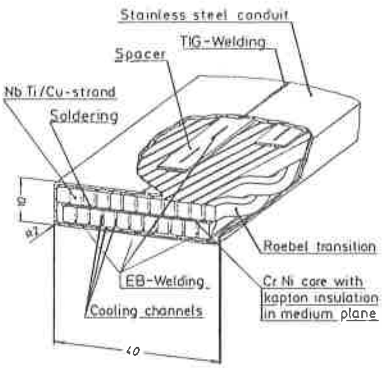


PF coil square superconductor /6/



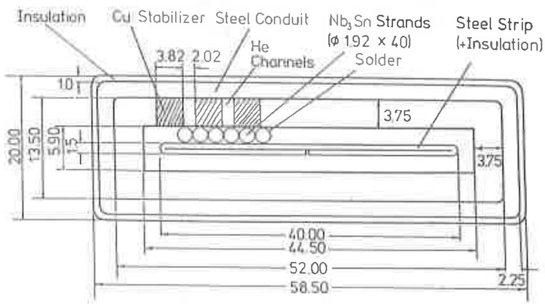
PF coil flat superconductor /6/

Composite cross sections of recently proposed superconductor cables



LCT superconductor NbTi

(existing technology)



TF coil flat superconductor /4,5/

Fig. 3: LCT-conductor (NbTi) and some recently proposed future superconductors (A15)

COMPOSITE CROSS SECTION

Required design data:

- **geometric arrangement (consideration of cooling, cryostability, mechanical integrity, fabrication, etc.)**
- **mechanical properties of individual components (S/C-strands, insulation, reinforcements, etc.)**

The shape of the "equivalent" stress-strain curve of a "homogenized" cross section

- is determined by the individual stress-strain curves and the geometric arrangement of the materials which build up the composite cross section
- determines the elastic strains after plastic forming and the remaining strains after elastic unloading as well as their corresponding residual stresses

APPLICATIONS

- Cable lift-off at radius jumps on the winding bobbin
- Conductor bending experiments
- Comparison between planar and nonplanar bending

Fig. 4: Current mechanical research topics in the development of future A15-superconductors

CONCLUSIONS

For the design of future large coils utilizing A15-type superconductors theoretical improvements are required to indicate with greater precision than today

— the implications of composite cross section layout

— the self-equilibrating stresses within the coil immediately after the completion of the manufacture

3. References

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