Dimensional changes measurement of Nb$_3$Sn Rutherford cables during heat-treatment using Digital Image Correlation

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**Nb₃Sn Heat Treatment RRP Wires**

- Nb₃Sn superconducting phase created at 650°C
- Heat treatment steps allow diffusion of Sn particles to diffuse into Nb through Cu

> These chemical phenomena induce deformations
• Nb$_3$Sn phase is brittle
• Coils are wound then reacted
• Differential strains between coil and tooling create non-negligible stresses
• Superconducting properties are stress sensitive

What are the deformations occurring during heat treatment in Nb$_3$Sn conductors?

Stress influence on superconducting properties [Ebermann P. and al. 2018]
DIGITAL IMAGE CORRELATION METHOD: CORRELI 3.0 PRINCIPLE

- Correli 3.0 software developed at LMT
- Allows a 2D in situ displacement measurement between 2 ≠ images → use of speckle
- 2 hypotheses:
  > Grey level is conserved
  > Displacement is the only difference between the images

Residual: \( \eta^2 = \int |f(\hat{x} + \vec{u}(\hat{x})) - g(\hat{x})|^2 d\hat{x} \)

\( f \) reference image
\( g \) deformed image

Solution displacement: \( \vec{u}(\hat{x}) = \arg\min_{\vec{u}} |\vec{u}(\eta)| \)

DIC speckle on Rutherford cable
Experimental setup: sample holder

- Sample holder vertically adjustable
- Jaws maintaining upper and down side of the cable and thermocouples
- Weight preventing the cable to collapse [Michels M., 2017]
- Sliding rods restraining cable from twisting and bending
**Experimental Setup**

- 5 windows allowing to take *in situ* pictures
- Compatible with tensile torsion compression machine (not used)
- Argon supply, $O_2\%$ maintained under 1 – 2%
- Vertical gradient of temperature from 1 to 0.5 K/cm

![Experimental setup: oven](image)

![Oven scheme](image)
GENERAL METHOD: NOISE MEASUREMENT ON COPPER CABLE

- Selecting Zone of Interest (ZoI) and mesh
- Displacement measurement at nodes
- Displacement interpolation in ZoI
- Noise estimation without loading
GENERAL METHOD: STRAIN MEASUREMENT ON COPPER CABLE

- Displacement measurement at nodes
- Displacement interpolation in ZoI
- Strain calculation, FEM
- Macroscopic strain determination

$u_y @ 215°C$

Strain calculation $\varepsilon_{yy} @ 215°C$

Macroscopic strain of Copper

$\varepsilon_{xx}$
$\varepsilon_{yy}$
$\varepsilon_{xy}$

Temperature (°C)
Study on Nb$_3$Sn Fresca II Rutherford cable

Average strain on both side of the cable

**Mesh**

**Macroscopic strain of Nb$_3$Sn Rutherford cable**
3 phenomena observed

1. Thermal expansion
2. Phases formation ➔ Mainly transversal @ 650°C
3. Copper annealing (literature) ➔ Mainly longitudinal
STRAND DISPLACEMENT WITHIN Nb$_3$Sn CABLE

- Strands independently meshed
- Split nodes at strands interfaces

➔ Need to measure the dimensional changes on a strand
In situ measurement on Rutherford cables

Rutherford cable model

Bimetallic strand model

Microscopic observations

Diffusion model

Presented here

Presented by A. Gorynin

On going work

Final goal

In situ measurement on strands

Macro

Meso

Micro
• 2D *in situ* Macroscopic strain measurement of Nb$_3$Sn Rutherford cables during heat treatment has been performed.

• 3 phenomena can be determined by these measurements:
  o Copper annealing
  o Phase transformation
  o Thermal dilatation

• Strand measurement and modelling are in progress in order to predict dimensional changes on ≠ Nb$_3$Sn conductors.
References


THANK YOU!
Upcoming: Strain measurements on Nb₃Sn strands

Missing $\varphi$ thermomechanical properties

For each $i$ phases in $\varphi$

$F(E_i, \nu_i, \alpha_i, f_i(t))$

Sub-element analysis (Arsenii’s Work)

Literature
3 Kinds of deformation

\[\varepsilon^e\] Mechanical strain, related to stress
\[\varepsilon^{th}\] Thermal strain, related to thermal expansion
\[\varepsilon^{ch}\] Chemical strain, related to phase changes

2 Area

\(Cu\) Copper releasing stresses from 150 to 200°C
\(\varphi\) Homogenized area, transversal isotropic