11T/MQXF task force
metallurgical inspection of MQXF coil CR108 LJ

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1. CR108 planes of interest an cuts

Metallographic examination – planes of interest

Dashed lines indicating the planes that have been prepared and examined: 1, 2, 3a, 3b and 4
2. CR108 cut 1 - metallographic examination

SC filaments and insulation state

A thorough examination revealed the presence of fine micro cracks, not always crossing totally the Nb3Sn crown, that seem to be located and confined to mid-plane at inner layer. Insulation exhibits large decohesion as well as crack metal to metal.

Conductor exhibiting micro cracks (several sub-elements can be impacted for an indicated location.)
2. CR108 cut 2 - metallographic examination

SC filaments and insulation state

A thorough examination revealed the presence of fine micro cracks, not always crossing totally the Nb3Sn crown, that seem to be located and confined to mid-plane at inner layer. Insulation exhibits large decohesion as well as crack metal to metal.

Conductor exhibiting micro cracks (several sub-elements can be impacted for an indicated location)
2. CR108 cut 3b - metallographic examination

SC filaments and insulation state

A thorough examination revealed very few events at mid-plane, inner layer. Insulation exhibits large cracks at rich resin area at titanium pole, decohesion as well as crack metal to metal.

Conductor exhibiting micro cracks (several sub-elements can be impacted for an indicated location)
2. CR108 cut 4 - metallographic examination

SC filaments and insulation state

A thorough examination revealed the presence of fine micro cracks, not always crossing totally the Nb3Sn crown, that seem to be located and confined to mid-plane at inner layer. Insulation exhibits mainly shrinkage cavities at interlayer.

Conductor exhibiting micro cracks (several sub-elements can be impacted for an indicated location)
3. CR108 – copper dissolution

Protocol

Planes previously examined have been subjected to concentrated HN03 diluted at 50% in water progressively with optical examination between each step. Approx. 400 µm/600 µm of copper has been removed by this means.
3. CR108 – copper dissolution

Optical examination

Several thorough examinations of the whole transverse cross sections between copper dissolution steps and after the last step revealed for cuts #1, #2 and #4 that:

The same and the only one strand at the extremity of the Rutherford cable adjacent to the pole block at inner layer exhibits collapsed SC filaments. The portion of the affected strand where filaments are broken/absent is even similar in the three cases. Cut 3b does not exhibit...
3. CR108 – copper dissolution

SEM examination

SEM examination allowed to highlight collapsed filaments and fractured SC sub-elements as never observed before. Filaments that seem still intact for the present example (cut 4): 74/108 are enumerated. Some filaments are missing, they have probably withdrew in rinsing water after etching.
3. CR108 – copper dissolution

SEM examination

Some filaments are missing (probably withdrew in rinsing water after etching); filaments that seem still intact:
- 75/108 are enumerated for cut 1
- 76/108 are enumerated for cut 2
3. CR108 cut 4 – copper dissolution

SEM examination

To the extent of present examination, fractured filaments exhibit transverse cracks that seem to be at the origin of the failure. Several strands exhibit complete breakage (plane transverse fractures).

Strands exhibiting complete breakage

Secondary cracks and steps

Strand exhibiting complete breakage

Fracture
Copper dissolution

Fracture: the fractured surface appears perpendicular to filament axis with a typical aspect of a brittle fracture. Grain size of SC phase can be appreciated.
3. CR108 cut 2 – copper dissolution

SEM examination

Highlight on fractured filament exhibiting transverse plane fracture: the fractured surface appears perpendicular to filament axis with a typical aspect of a brittle fracture. Grain size of SC phase can be appreciated.
4. CR108 cut 4 – longitudinal cut

Extraction of the VOI

Extraction of the VOI containing the cables at pole block inner layer has been carried out by DWS.
Progressive polishing with intermediate observation steps has been performed to access to 1\textsuperscript{st} and 2\textsuperscript{nd} row’s midplane of the first Rutherford cable. To the extent of present examinations, only the 1\textsuperscript{st} row’s midplane exhibits events at superconductive filaments.
Examination of the whole surface revealed large cracks with clearly separated filaments at similar locations of several strands in correspondence to vicinity of titanium poles.

Opened and cracked filaments seem to exhibit a V shape which could indicate bending issue.
Local analyses carried out with a SEM equipped with an EDS detector at indicated strand.

Cu and sometimes Sn are identified in between cracked filaments.

Nb3Sn phase is well identified.
Local analyses carried out with a SEM indicated strand. Accessible fractured surfaces reveal aspect and propagation plane in accordance with what has been observed on transverse cross sections at collapsed filaments.
4. CR108 cut 4 – longitudinal cut

Continuation of events from 1st row’s midplane to the 2nd row’s midplane

Cable thin edge: Sonia PEGGIANI / Master thesis « Analysis of Nb3Sn Rutherford cable production and strand deformations »
Continuation of events from 1st row’s midplane to the 2nd row’s midplane

Depth advance ≈ 2.52 mm
4. CR108 cut – longitudinal cut

Continuation of events from 1st row’s midplane to the 2nd row’s midplane

Indication of plastic deformation

1st row’s midplane

2nd row’s midplane

≈2,65 mm

The fractured filaments observed at 1st row’s midplane belong to the same strand that was examined on the prior transverse cross section containing collapsed filaments.

Continuation of significant events is established on same strand from a row to the second row of the Rutherford cable.
4. Conclusion and discussion

- Metallographic examination revealed for all cuts the presence of fine micro cracks, not always crossing the Nb3Sn crown, at inner layer in great majority but not especially at pole block. Insulation exhibits, in addition to shrinkage cavities, decohesion and crack metal to metal for 3/4 examined cuts,
- Progressive dissolution of the copper matrix allowed to free potentially damaged filaments in the continuation of the examined planes with the amazing following result:

  The same and single strand at the extremity of the Rutherford cable adjacent to the pole block at inner layer exhibits collapsed SC filaments for cuts #1, #2 and #4

- To the extent of present examination, fractured filaments exhibit transverse breakage in several cases complete that seems to be at the origin of the failure.

  - Statistics (1 / 2000 strands)
  - 3 planes of interest distant of several centimetres exhibit the same phenomenology
  - The affected strand is part of the cable related to the quench (according to the voltage stabs)

- A longitudinal cut, in block containing the cut 4, revealed on the 1st row’s midplane, of the Rutherford cable in cause, in the specific position of the twist pitch :

  Several fractured filaments exhibit transverse breakage with fractured surfaces and propagation planes in accordance with what has been observed on transverse cross sections at collapsed filaments. Continuation of significant events is established on same strand from a row to the second row of the Rutherford cable involving quench.
4. Conclusion and discussion

• Fractured filaments exhibit transverse cracks not easily revealed by an examination on a “conventional” transverse cross section. These cracks appear, by their morphology and their propagation plane, different from the micro cracks usually observed on transverse cross sections.

• There is concordance between observations carried out on transverse cross sections and longitudinal cut:
  
  ➢ Cracked filaments appear only on twist pitch close to titanium poles (stress concentration at this specific location)
  ➢ Affected filaments exhibit plane transverse breakage with transgranular aspect at fractured surfaces
  ➢ Cracked filaments observed in longitudinal cut seem to draw a V shape that could indicate bending on axial direction

The present results would indicate that bending in the axial direction and stress concentration on the strand close to titanium poles had cause the present damages at superconductive filaments that led to quench of the coil.