Strain variation in NbTi filaments

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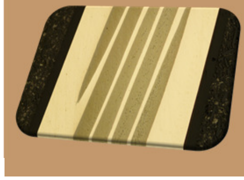
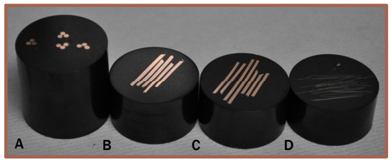


Abstract

NbTi superconducting wires are used in a wide variety of magnet systems to carry large electric currents and produce large magnetic fields of 1 – 5 T. These wires, consisting of NbTi filaments located within the host Cu wire, need to perform at engineered levels for optimal performance of the device. To do this, the wires are drawn to carefully-specified levels of strain, which causes precipitation of an α-Ti phase that dramatically improves the current-carrying capacity of the superconductor. To assess how uniformly the strain is being applied to NbTi filaments within a composite wire, we have developed an image analysis technique to identify geometrical variations among filaments in a wire and between wires from different starting billets. In this study we use scanning electron microscopy (SEM) to perform the image analysis on two separate billets of the same initial design. One billet is found to have relatively uniform strain variations amongst the filaments, while the second billet is found to have a highly non-uniform distribution, as measured by geometric variables. This relatively simple approach can provide feedback to the wire manufacturer regarding the stability of the manufacturing process.

Sample preparation

The samples were prepared by segmenting sections of wire sample and mounting them within metallographic pucks. They were then ground and polished to a mirror like finish for SEM/EDS analysis. Samples were mounted both longitudinally and transversely into the puck for SEM/EDS imaging.

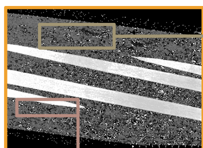


Puck A – Transversely mounted wires.
Puck B & C – Longitudinally mounted wires.
Puck D – Longitudinally mounted filaments.

Extrusion example

Notice that in A (slow extrusion) the filaments are smooth and even while in B (fast extrusion) they have significant deformities due shear stresses.

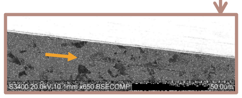
Visual examination of NbTi wires

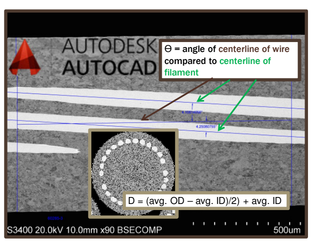


Element	Wt.%	% Error
Al	0.05	+/- 0.01
Cu	99.94	+/- 0.21

EDS showed all Cu compositions to be within +/- 1%.

Longitudinal overview image. Wires are internally twisted for electromagnetic stability.



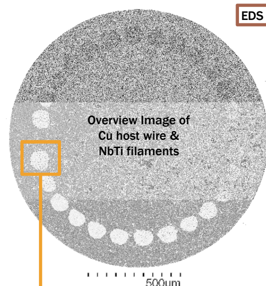


Lack of bonding defect is pointed out. Nb barrier for NbTi filament is clean and intact.

Sample ID – Pitch in mm
A – 45.4 mm
B – 41.9 mm
C – 46.6 mm

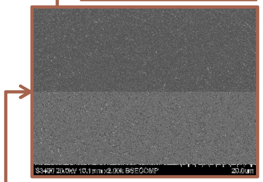
$Pitch = (\pi D)\tan\alpha \cdot \cos(90° - \varphi)$
$\varphi = \cos^{-1}(d/R)$, $\alpha = 90° - \Theta$,
D = dia. of ring of filaments,
$R = D/2$, d = filament diameter

Quantitative image analysis

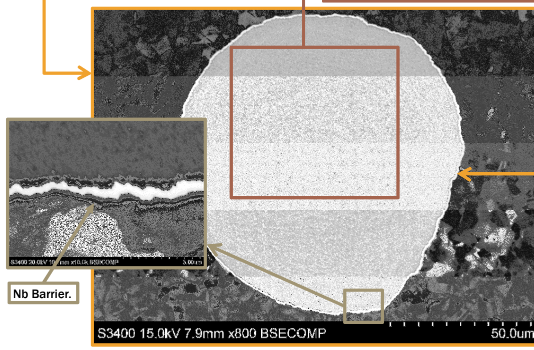


EDS showed all NbTi compositions to be within +/- 1%.

Element	Wt.%	% Error
Ti	45.82	+/- 0.16
Nb	53.63	+/- 0.17



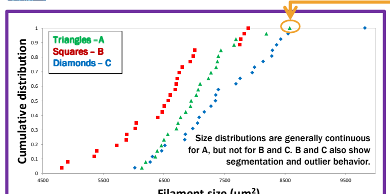
Note: "Tree ring" pattern from vacuum arc remelting process.



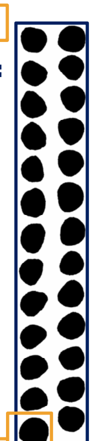
Nb Barrier.

Cu grain structure is recrystallized with subsequent evidence of cold work. Nb barrier prevents Cu contamination of the NbTi and appears intact here.

Ps + reindeer graphics =

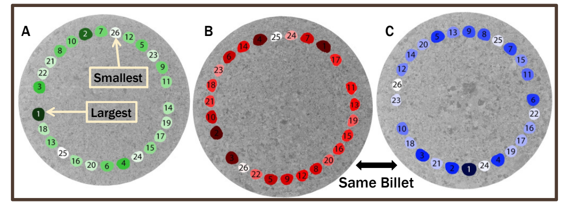


Filament size	A	B	C
Average [μm²]	7041	6480	7473
St. dev. [μm²]	590	838	875
Coeff. variation	8.4%	12.9%	11.7%
Aspect ratio	**A**	**B**	**C**
Average	1.16	1.26	1.18
St. dev.	0.065	0.092	0.076
Coeff. variation	5.6%	7.3%	6.4%
Roundness	**A**	**B**	**C**
Average	0.851	0.776	0.835
St. dev.	0.045	0.060	0.051
Coeff. variation	5.3%	7.7%	6.1%

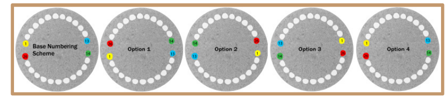


Billet comparison

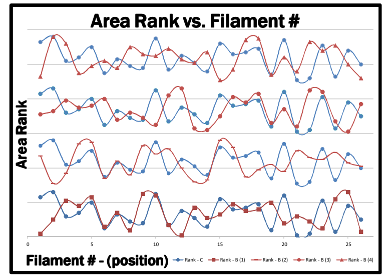
Filament size variation quantified for three samples from two billets.



Variation in size distribution is evidence of moderate sausaging.



Possible comparative numbering schemes for the filaments.



Sample C compared to 4 possible Sample B results.

Good matching between samples B and C would indicate the size distribution was present in the starting billet.

Poor matching between the samples would indicate the size distribution developed during extrusion/drawing.

Conclusion

- The percent variation of filament area within each sample wire: A – 33%, B – 48%, C – 48%.
- Samples B and C came from same billet and show larger (and similar) percentage variation. Their filament average areas differ by 8% relative to each other, evidence of moderate sausaging.
- The variation does not follow a common pattern around the twisted wire, i.e. the variation was not present in the original billet but rather developed during wire extrusion/drawing process.
- Variation in performance does not appear to be due to lack of chemical homogeneity.

Future Work

The literature shows that:

Strain Variation = Performance Variation

And since the filaments start at the same size in the original billet:

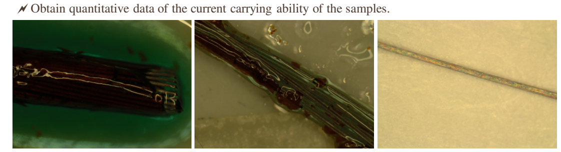
Strain Variation = Geometric Variation

So our technique provides a fast quality control check to show that:

Geometric Variation = Performance Variation

Plans for continued work:

- Development of a longitudinal filament image analysis methods.
- Micro-hardness and tensile testing of filaments at 293K and 77K.
- Obtain quantitative data of the current carrying ability of the samples.



Wire and resulting filaments in a 50% by volume HNO_3 Etch bath.

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