RRP & PIT Deformation & RRR Comparison:

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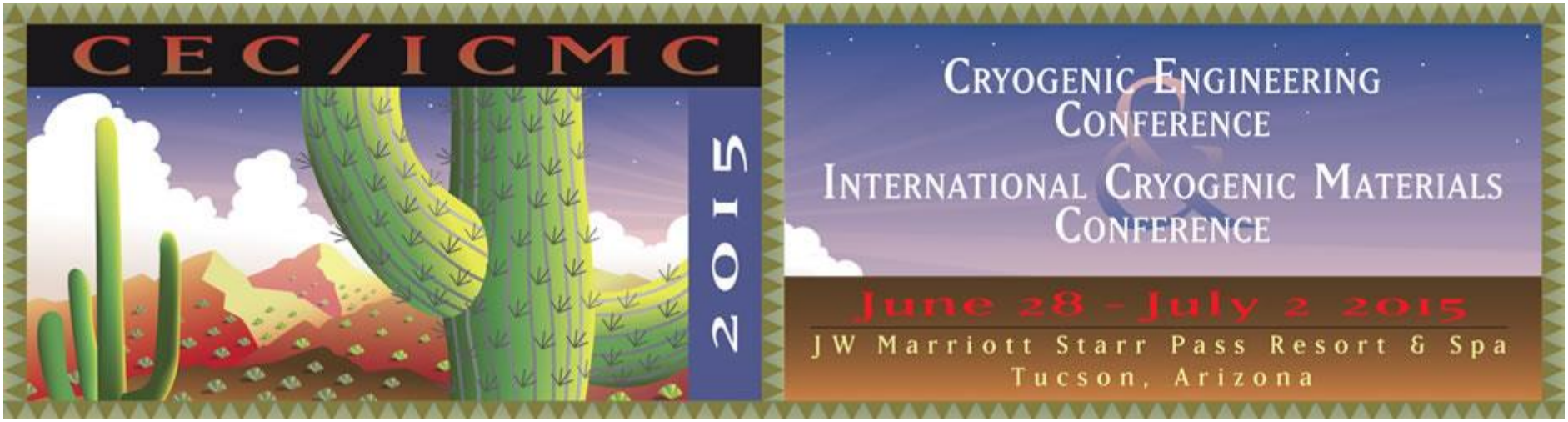
ASC – NHMFL – FSU



Acknowledgements

This research was funded by the Department of Energy; Office of High Energy Physics under Grant #: DE-SC0012083

RRP® strand provided under the DOE Conductor Development Program that is managed by D. Dietderich of the Lawrence Berkeley Laboratory.

PIT strand was supplied to us by the US LHC Accelerator Research Program (LARP), which is a BNL, FNAL, LBNL, and SLAC collaboration with CERN for the High Luminosity LHC program: http://www.uslarp.org/

Experiment

What have we done?

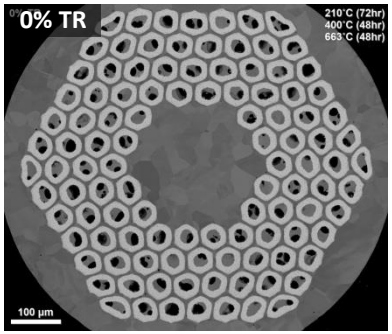
- → A quantitative study of the shape and position of filaments (sub-elements) after rolling lengths of unreacted PIT & RRP® round wires to simulate cabling deformation.
- → RRR values taken in varying stages of deformation.
- → Diffusion Barrier leakages quantified and compared to filament distortion.

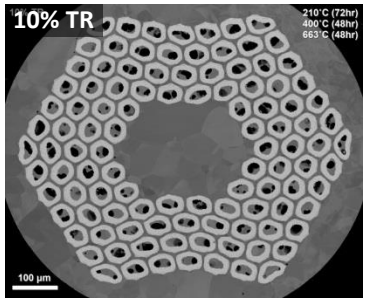
Why?

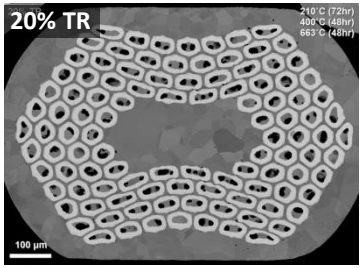
- → To benchmark the deformation to determine a limit past which unacceptable damage has occurred, and for discussion on how to best limit this damage

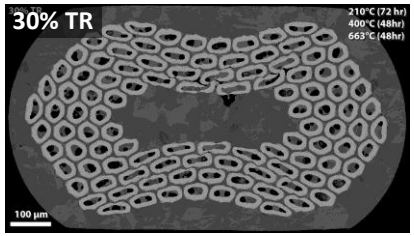
So What?

- → We find that a critical distortion occurs for thickness reductions between 10 and 20%.
- → In this range, the filament shapes transition from higher aspect ratio in outer filament rings to much larger aspect ratios in inner filament rings, especially in the vicinity of the strong 45˚ shear bands imposed by the rolling
- → Comparison with RRR gives direct performance comparison of deformed strands.









Previous Work

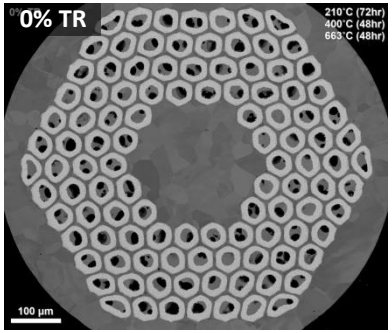
Rolling Experiments to simulate Rutherford cabling:

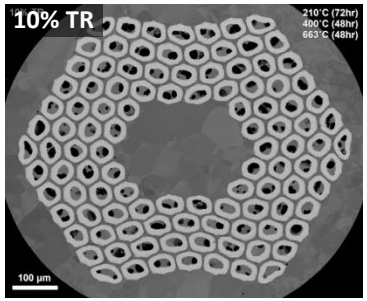
- Turrioni D, Barzi E, Bossert M, Kashikhin V V, Kikuchi A, Yamada R, and Zlobin A V 2007 **Study of Effects of Deformation in Nb3Sn Multifilamentary Strands** *IEEE Transactions on Applied Superconductivity* **17** 2710–3
  - → "A procedure that makes use of both microscopic analysis and macroscopic measurements was established to study effects of deformation in brittle superconducting strands."

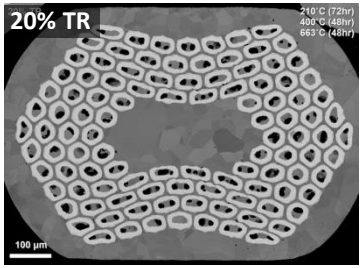
- Ghosh A K, Cooley L D, Dietderich D R, and Sun L 2008 **Transport and Magnetization Properties of Rolled RRP Nb_3Sn Strands** *IEEE Transactions on Applied Superconductivity*, vol. 18, no. 2, pp. 993–996
  - → Carried out transport, magnetization, and RRR measurements on rolled RRP strands. Showed that RRR is the most greatly affected.

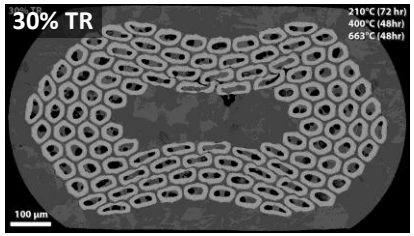
- Barzi E, Turrioni D, and Zlobin A V 2014 **Progress in RRP Strand Studies and Rutherford Cable Development at FNAL** *IEEE Transactions on Applied Superconductivity* **24** 1–8
  - → Used flat rolling to test electrical performance of conductors after varying degrees of deformation.

In this work, we build upon previously used methods with a targeted focus on the shape change in the individual filaments (PIT) or sub-elements (RRP®).



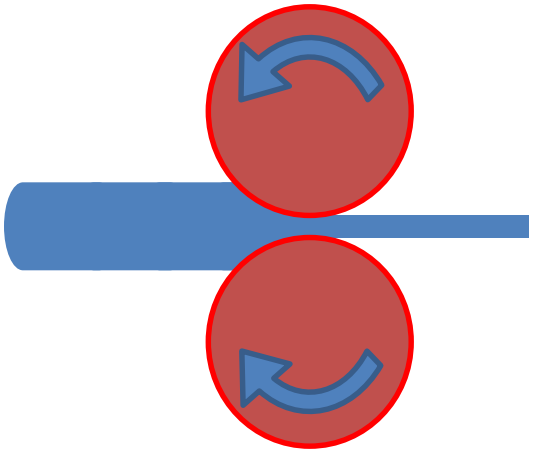




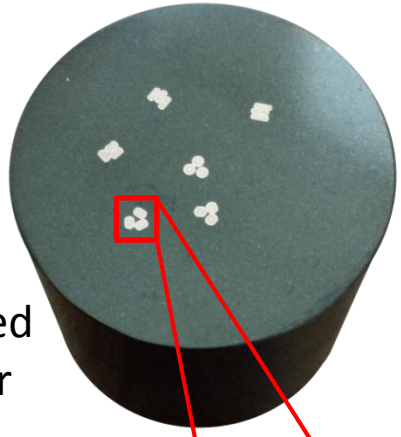


Experimental Procedure

Strand rolled in ~5% increments



- Samples taken at 10% increments: 10, 20, & 30% Thickness Reduction (TR)
- Wires then heat treated:
  → Treatments in table below
- Samples then polished and imaged in SEM using Backscatter detector

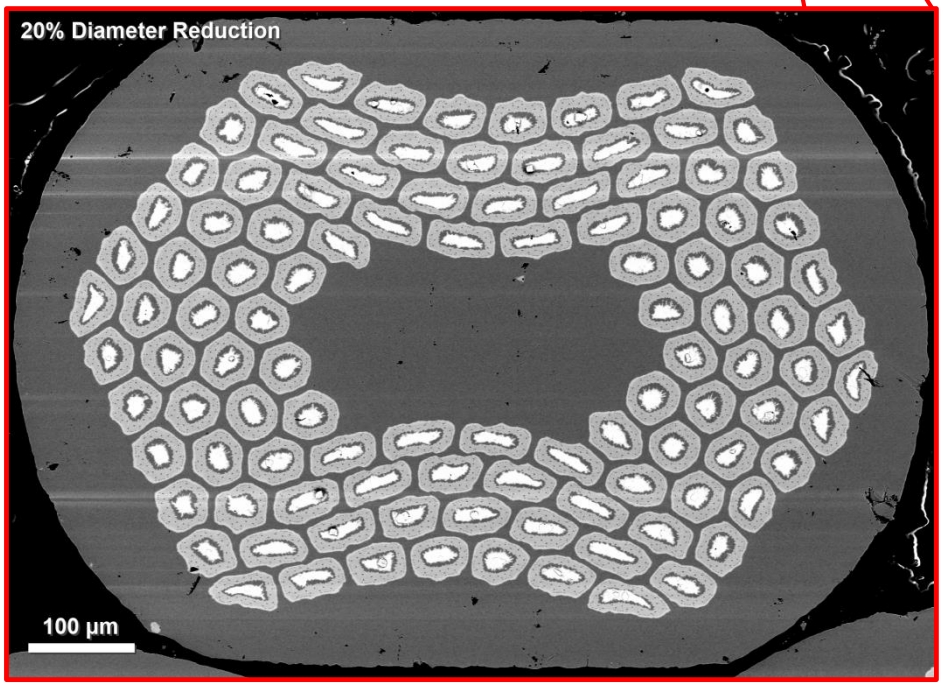


WIRE SPECS:

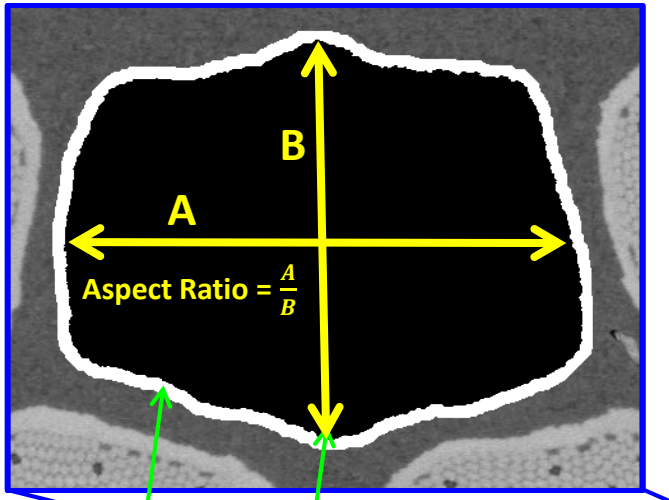
RRP 108/127
Manufacturer: **OST**
Supplier: DOE /CDP

PIT 192/217
Manufacturer: **Bruker**
Supplier: DOE /CDP

		Standard Sn		Reduced Sn	
Name	**PIT**	**RRP-S1**	**RRP-S2**	**RRP-R1**	**RRP-R2**
Billet #	31284	14895	14943	14896	14982
d_0 (mm)	0.784	0.778	0.778	0.778	0.778
Nb/Sn	-	3.4	3.4	3.6	3.6
RRR	80	259	207	317	481
H.T.	620˚C (100hr) 640˚C (90hr)	210˚C (72hr) 400˚C (48hr) 640˚C (48hr)	210˚C (72hr) 400˚C (48hr) 640˚C (48hr)	210˚C (72hr) 400˚C (48hr) 663˚C (48hr)	210˚C (72hr) 400˚C (48hr) 663˚C (48hr)

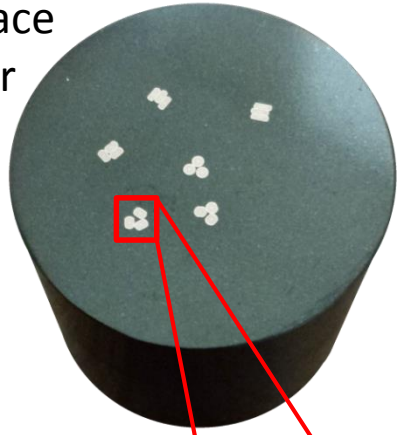


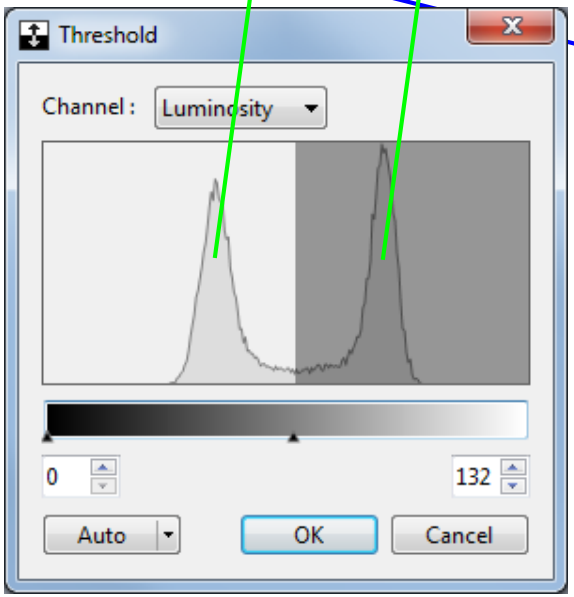
Filament Shape Definition



Steps:

- Isolate DB and Cu interface
- Threshold between color values
- Subtract Cu portion to isolate filament shape
- Use image analysis to compile filament data





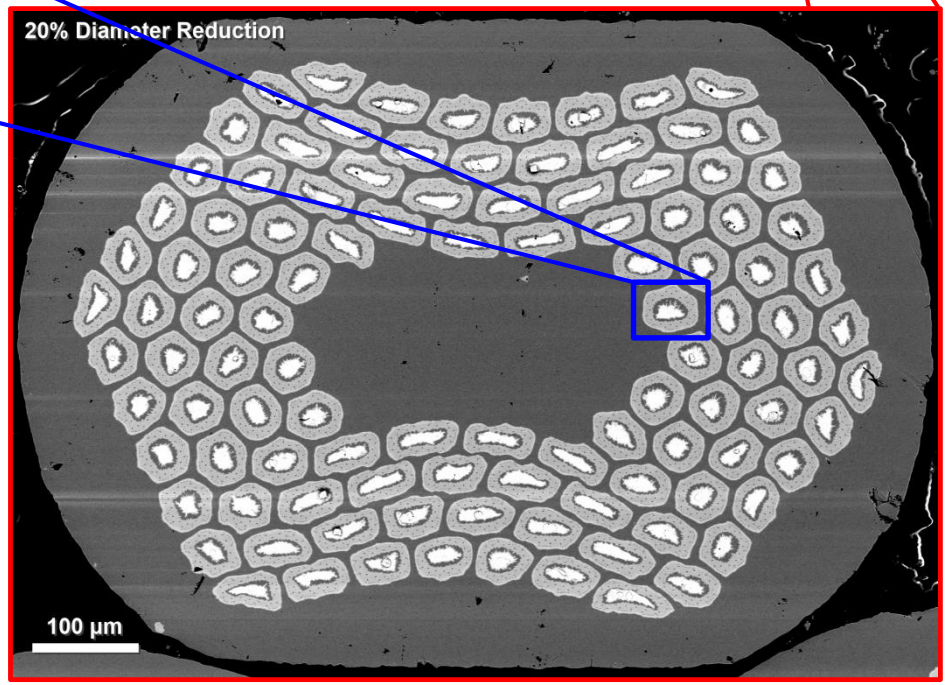
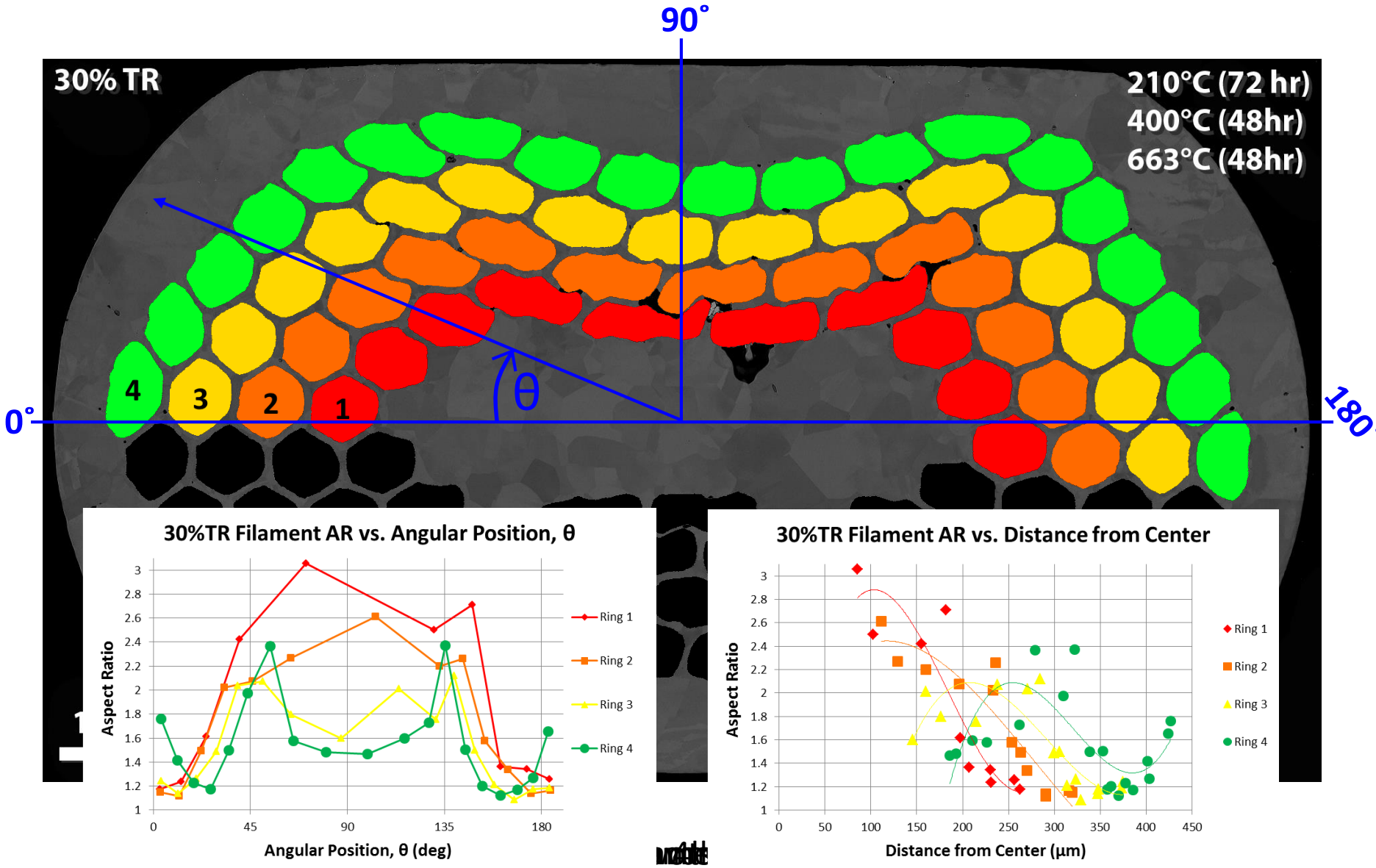
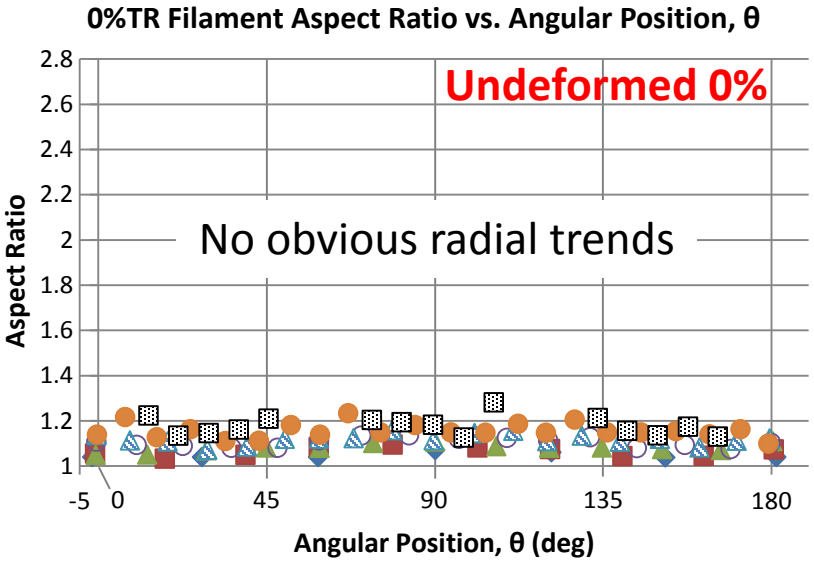
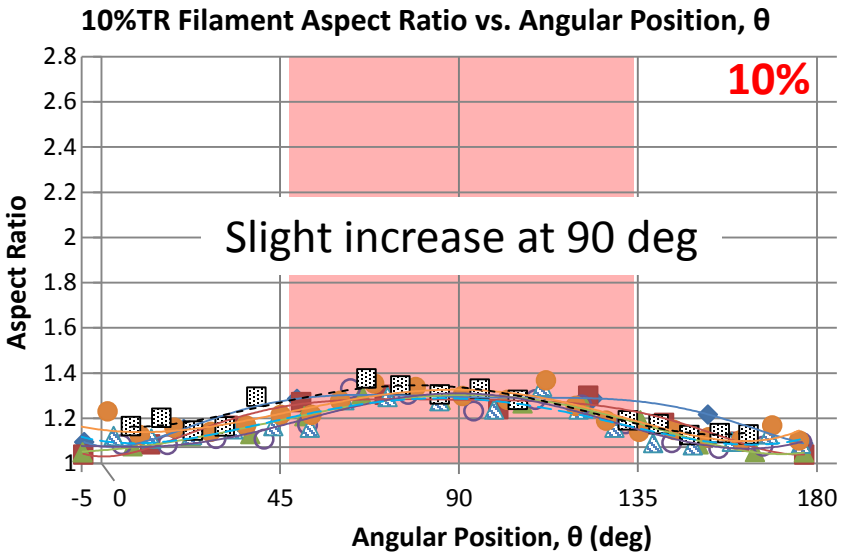


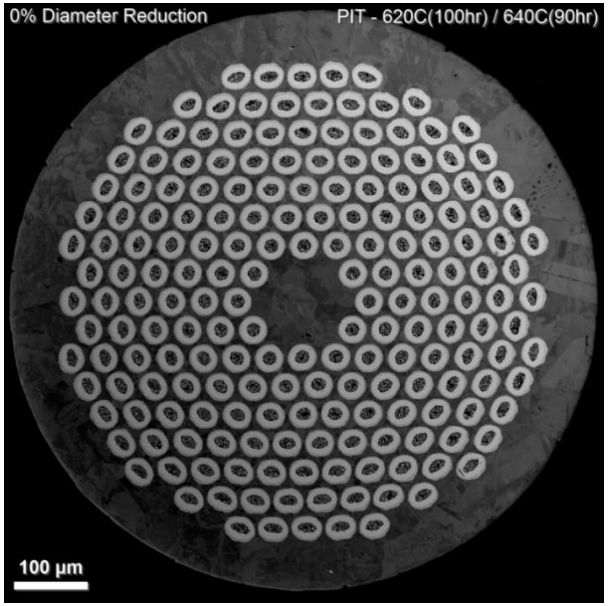
Image Analysis Techniques on Full Strand

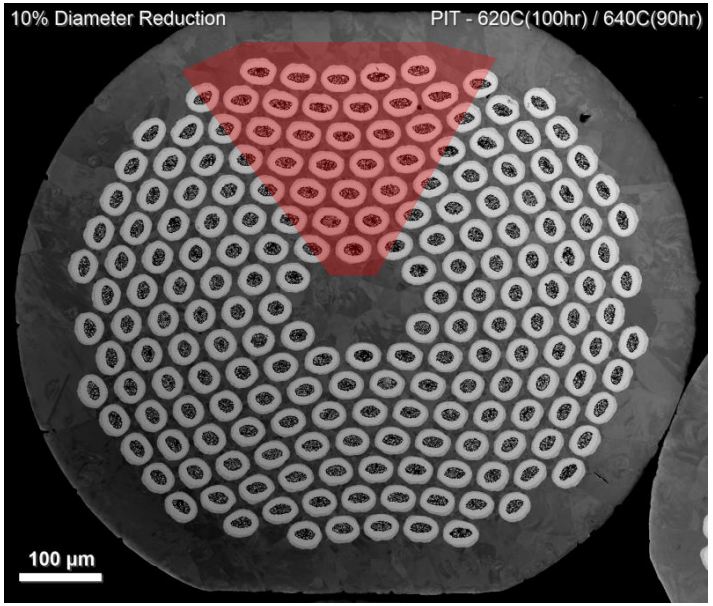


PIT – Deformation vs. Angular Position

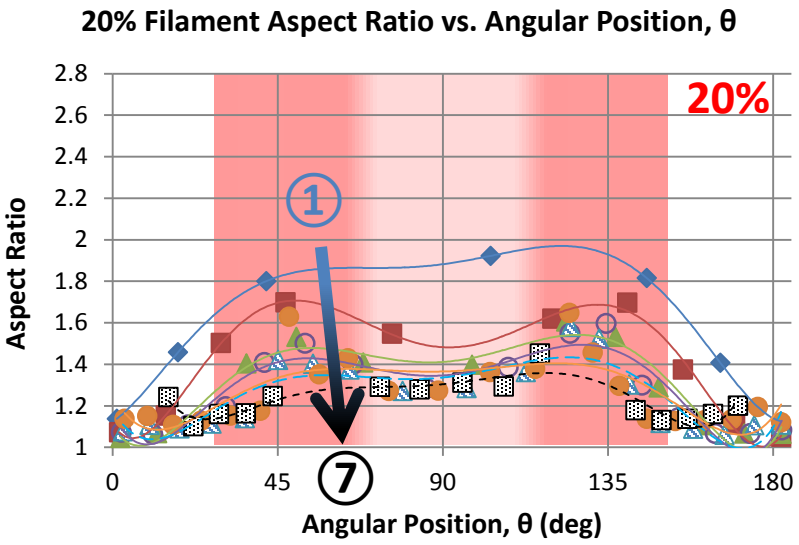


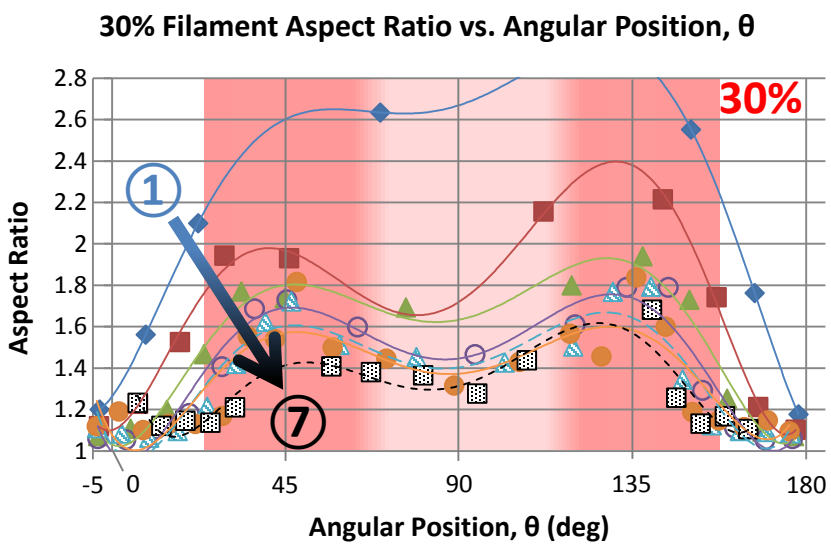


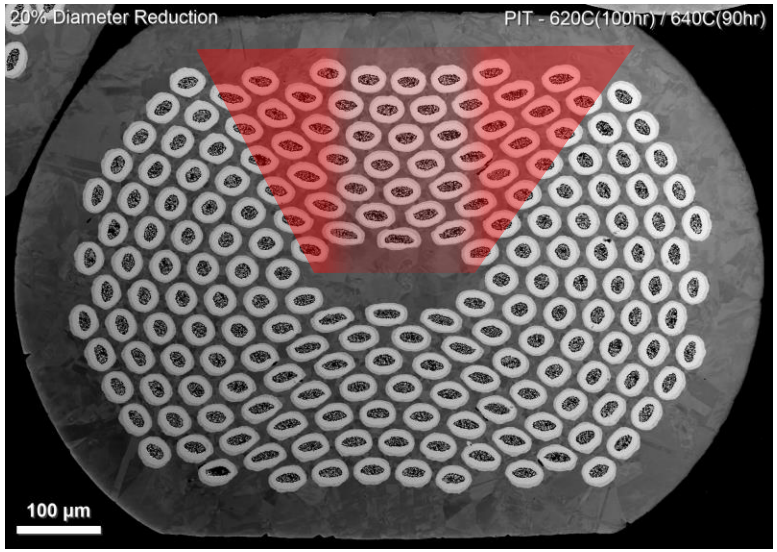


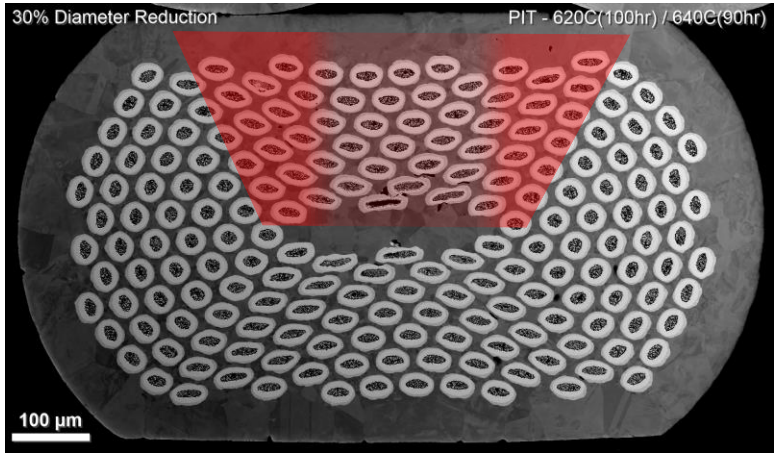


PIT – Shear Bands of Large Deformation

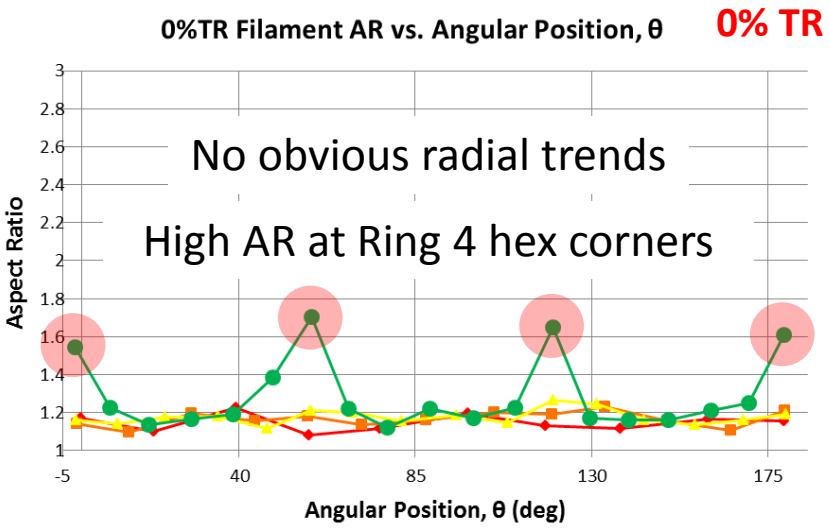


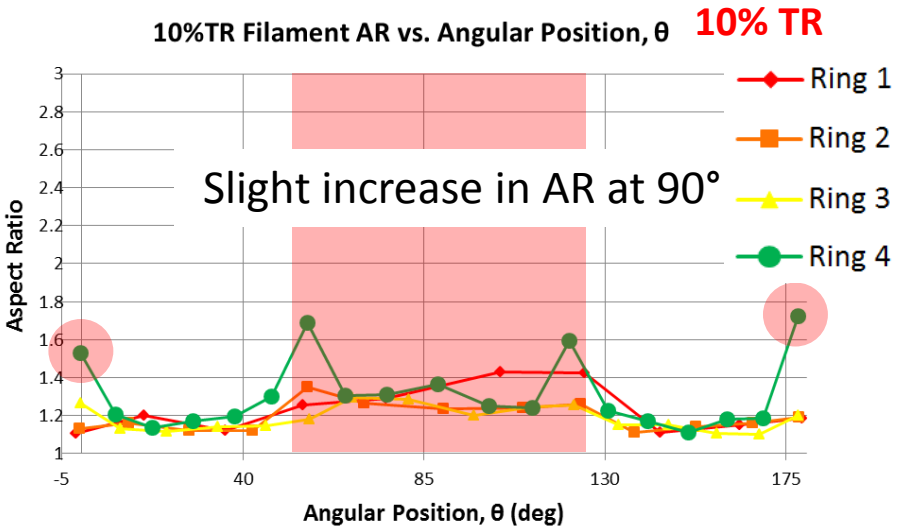


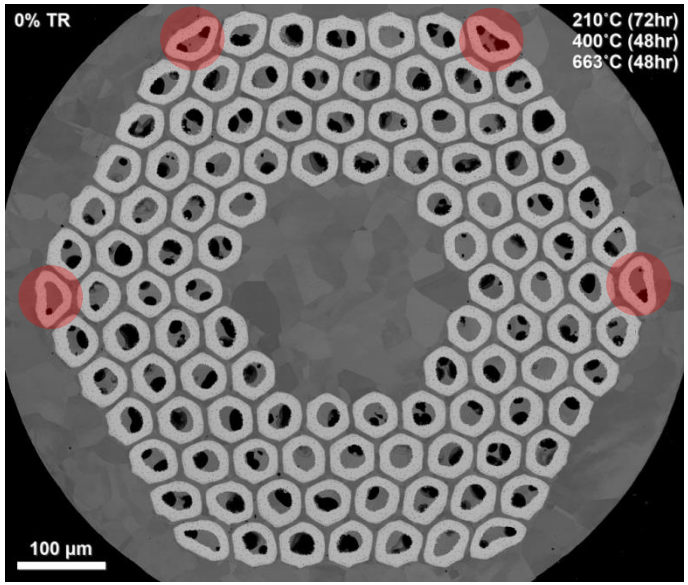


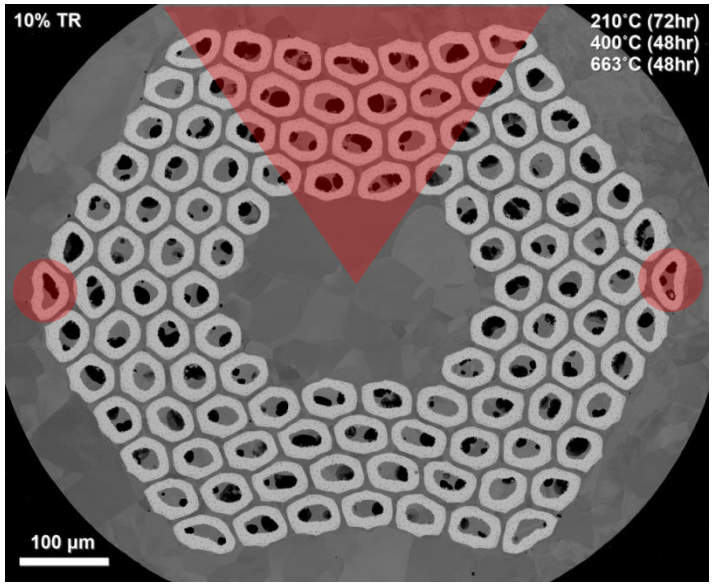


RRP – Deformation vs. Angular Position

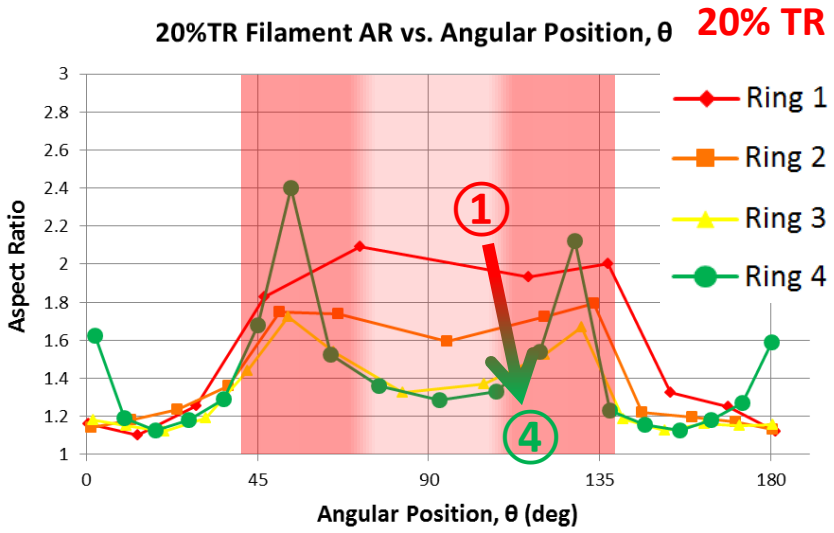


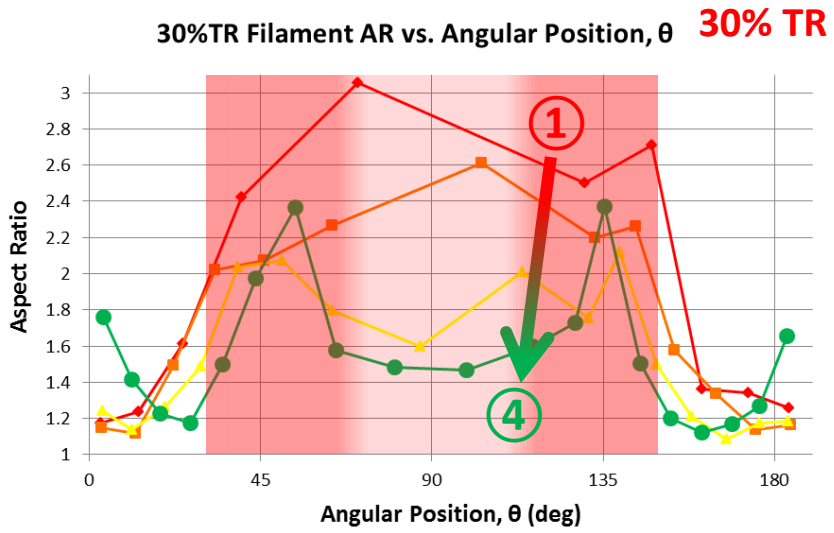


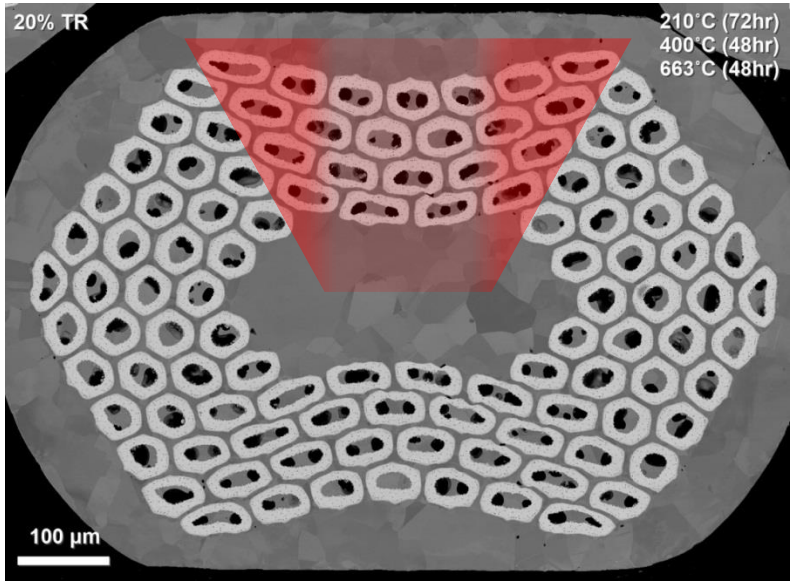


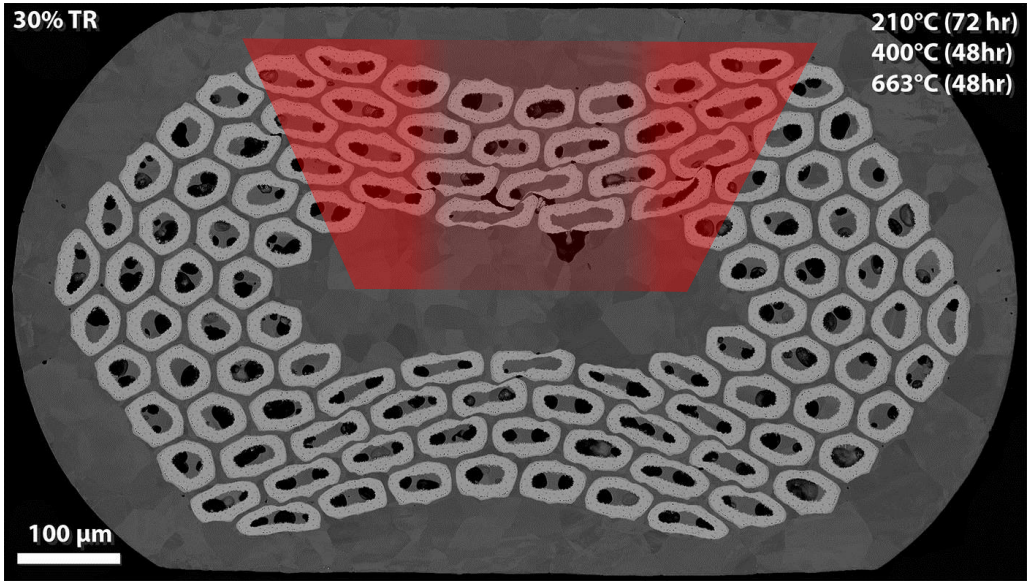


RRP Aspect Ratio – Shear Bands at higher TR

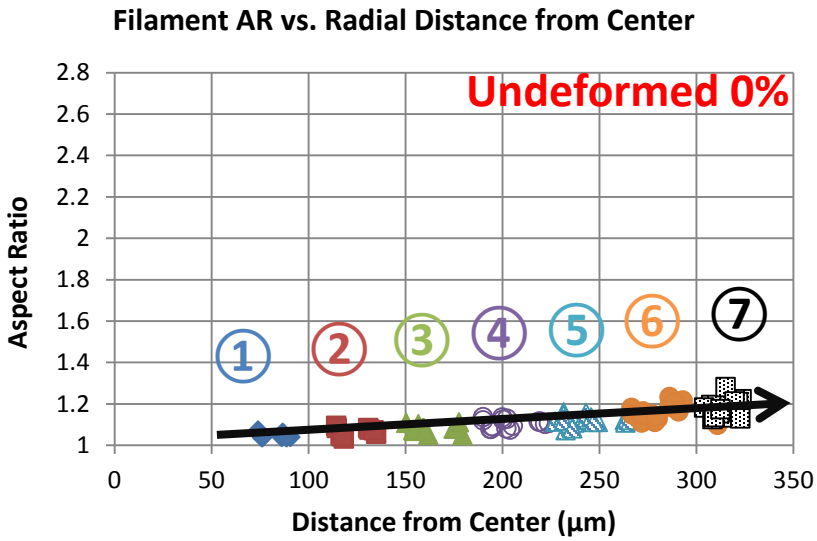


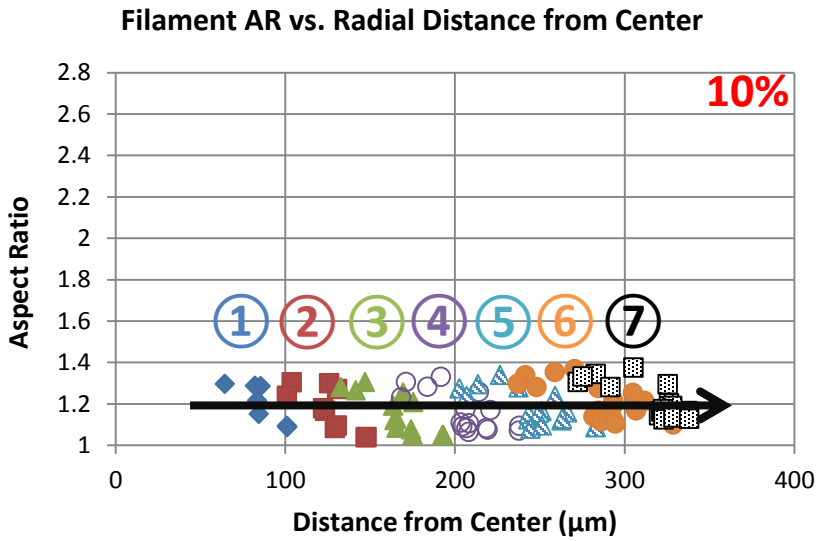


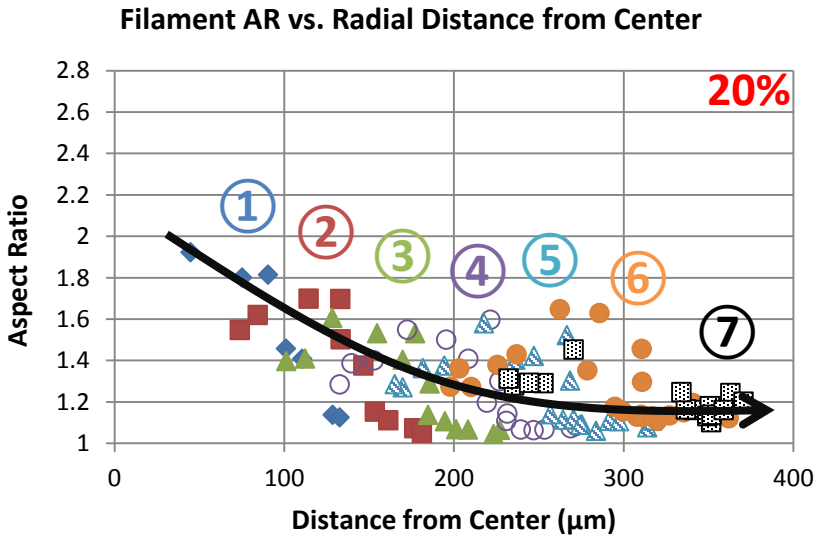


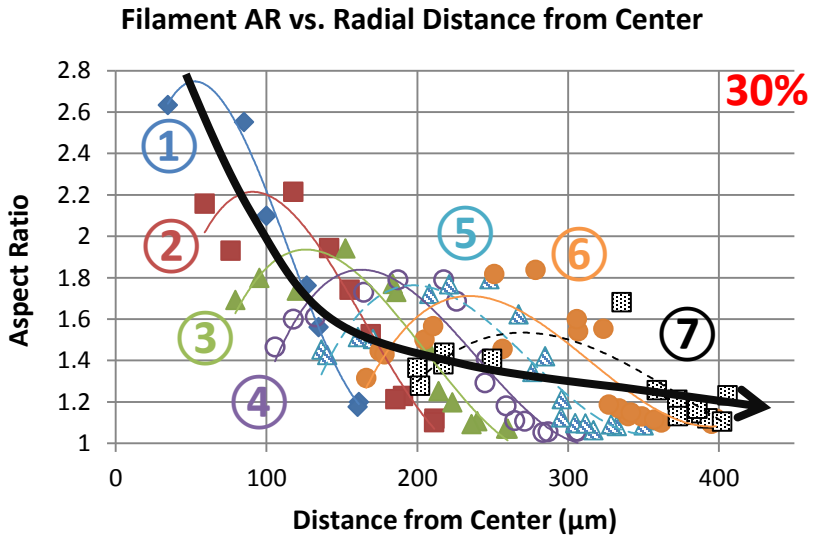


PIT – Inner Filament Deformation Upon Rolling

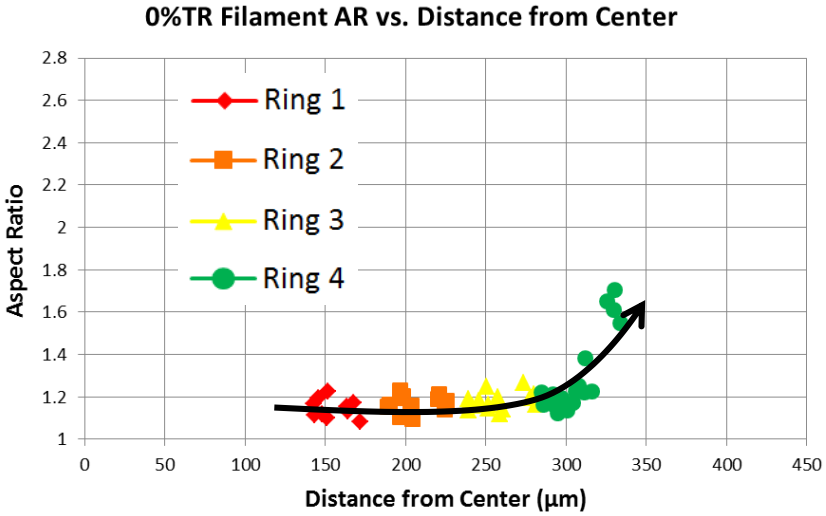


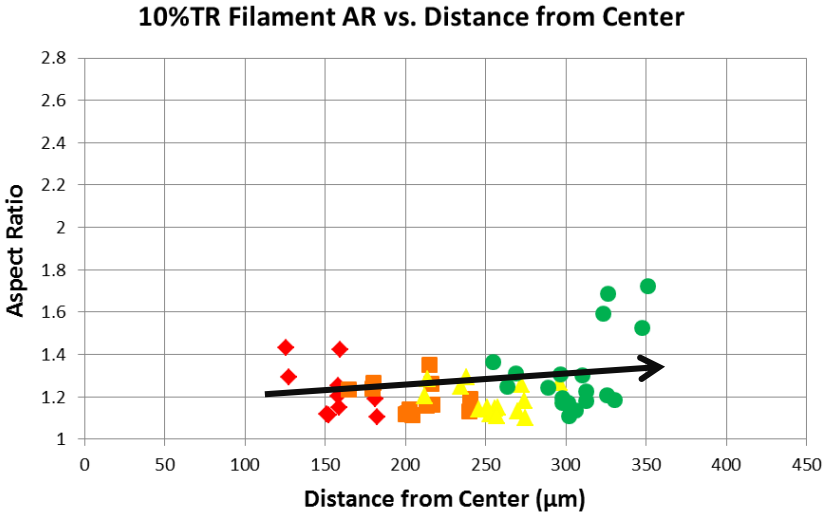


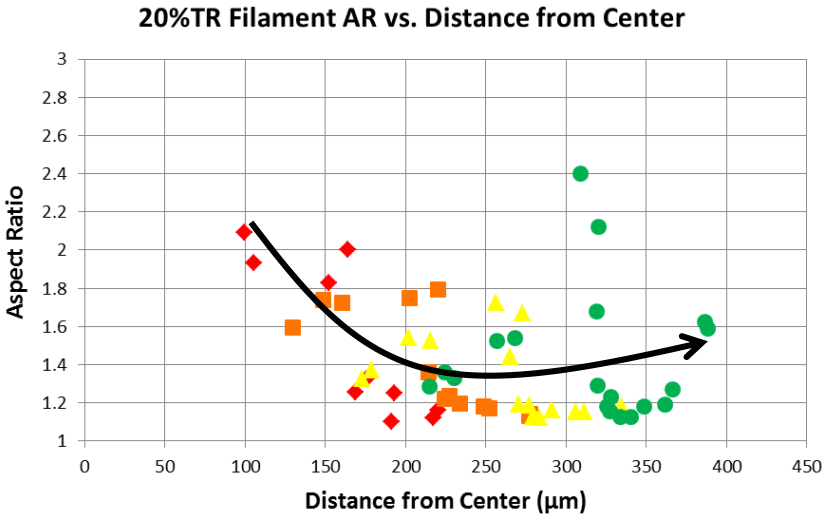


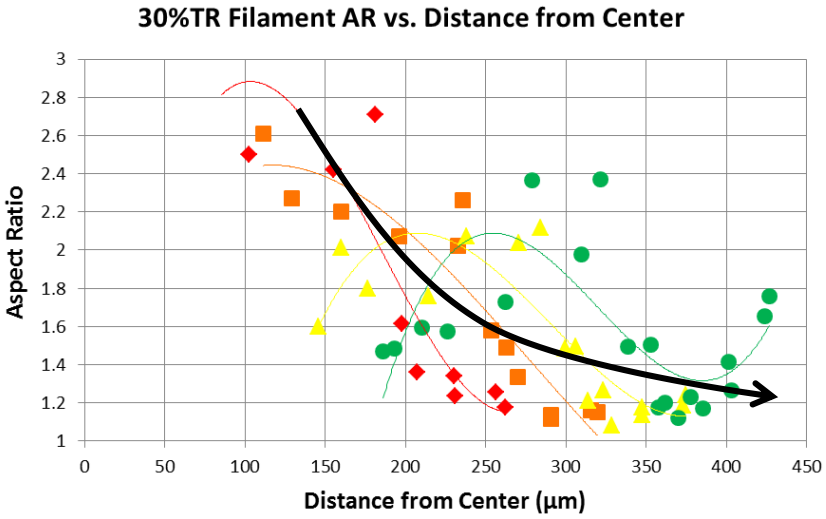


RRP – Inner Filament Deformation Upon Rolling







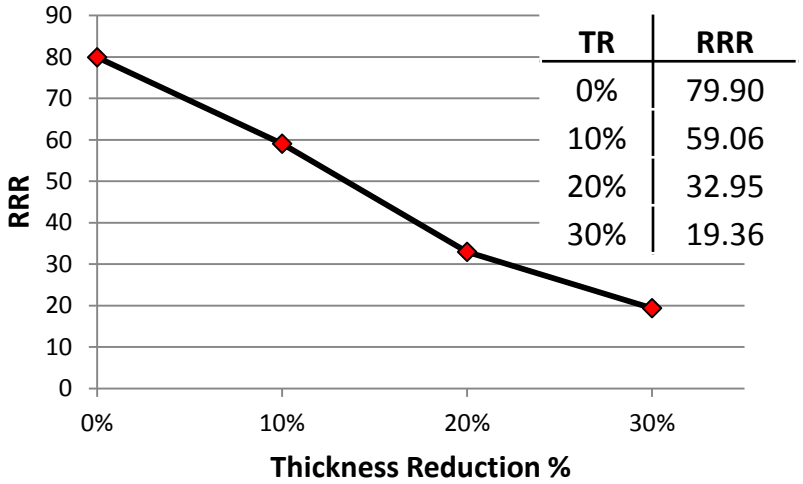


PIT Damage Trends – DB Leakages

of DB Breakthroughs in Rings

Ring #	0% TR	10% TR	20% TR	30% TR
1	0	1	1	3
2	0	0	1	3
3	0	0	3	1
4	0	0	2	2
5	0	0	0	2
6	0	3	2	1
7	0	1	1	0
Total	0	5	10	12

PIT RRR- 620C(100hr)/640C(90hr)

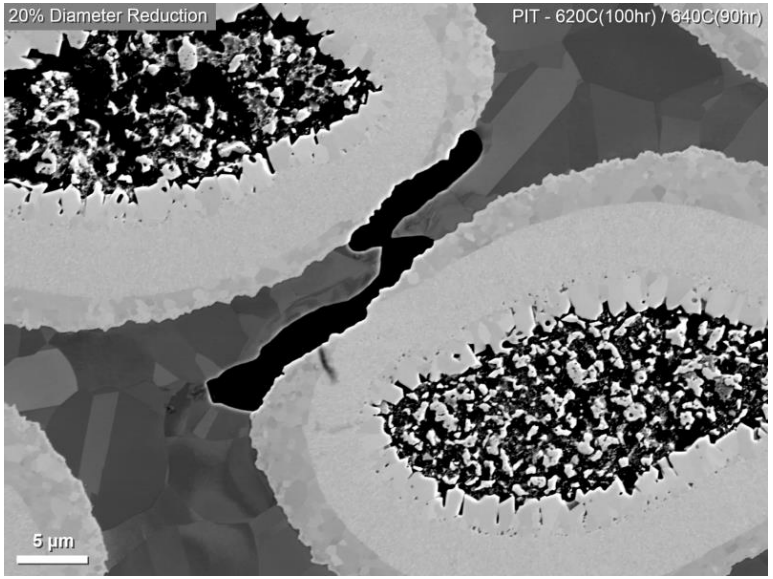


TR	RRR
0%	79.90
10%	59.06
20%	32.95
30%	19.36

Two general trends are seen in both the table and graph.

Obvious: breakthroughs increase with increasing thickness reduction

Less obvious: Breakthroughs are favored on inner rings as %TR increases



Diffusion Barrier Sn leakage in 20% TR sample indicated by Kirkendall void, and A15 formation on outer DB

***Note:** Breakthroughs counted from entire cross-section (not just top half)

RRP Damage Trends - DB Leakages

Standard Sn

14895	Thickness Reduction			
Ring	0%	10%	20%	30%
1	0	0	1	6
2	0	0	2	5
3	1	0	3	1
4	1	0	0	2
Total -->	2	0	6	14

14943	Thickness Reduction			
Ring	0%	10%	20%	30%
1	2	0	1	5
2	0	0	4	4
3	0	0	2	4
4	0	0	1	3
Total -->	2	0	8	16

Reduced Sn

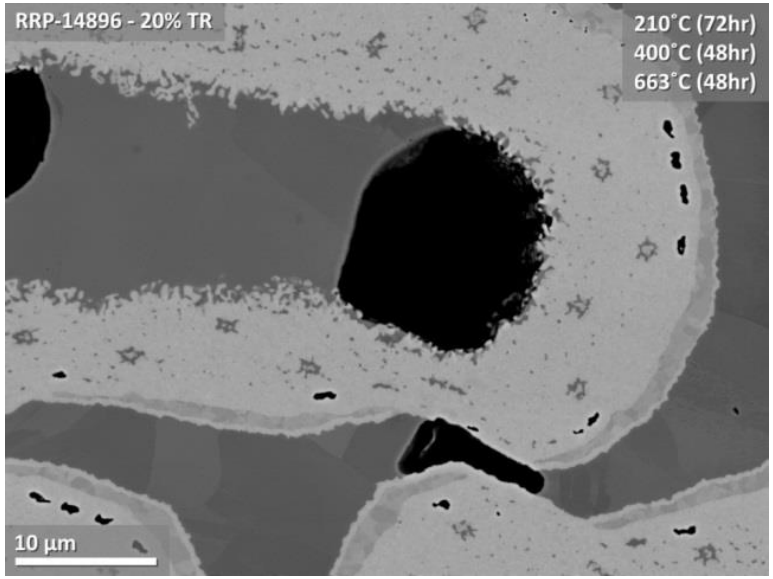
14896	Thickness Reduction			
Ring	0%	10%	20%	30%
1	0	1	1	5
2	0	0	1	7
3	0	0	0	2
4	0	0	0	1
Total -->	0	1	2	15

14982	Thickness Reduction			
Ring	0%	10%	20%	30%
1	0	0	2	4
2	0	0	4	7
3	0	0	2	4
4	0	0	1	2
Total -->	0	0	9	17

Again, two general trends are observed.

Obvious: breakthroughs increase with increasing thickness reduction

Less obvious: Breakthroughs are favored on inner rings as %TR increases



Diffusion Barrier Sn leakage in 10% TR sample indicated by Kirkendall void, and A15 formation on outer DB

Damage Trends – RRR degradation @ 20% TR

Good ≤ 10% **Bad ≥ 20%**

Standard Sn

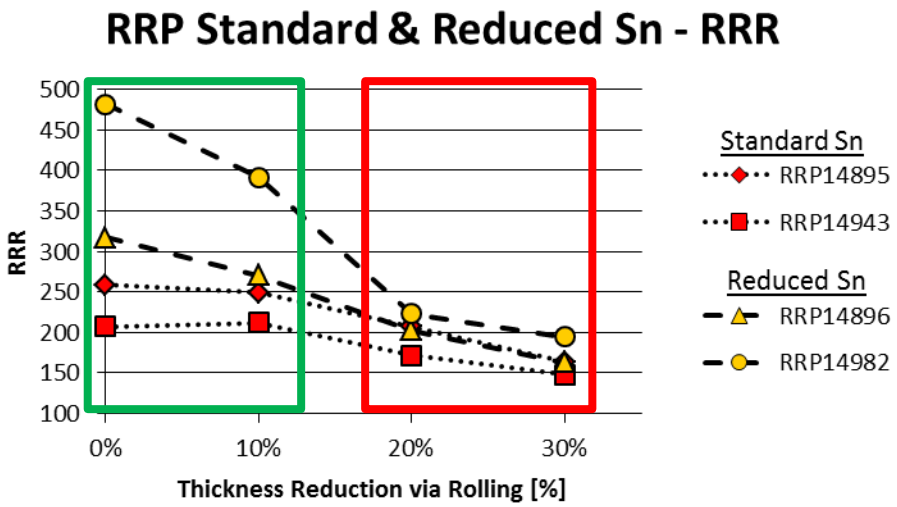
14895	Thickness Reduction			
Ring	0%	10%	20%	30%
1	0	0	1	6
2	0	0	2	5
3	1	0	3	1
4	1	0	0	2
Total -->	2	0	6	14

14943	Thickness Reduction			
Ring	0%	10%	20%	30%
1	2	0	1	5
2	0	0	4	4
3	0	0	2	4
4	0	0	1	3
Total -->	2	0	8	16

Reduced Sn

14896	Thickness Reduction			
Ring	0%	10%	20%	30%
1	0	1	1	5
2	0	0	1	7
3	0	0	0	2
4	0	0	0	1
Total -->	0	1	2	15

14982	Thickness Reduction			
Ring	0%	10%	20%	30%
1	0	0	2	4
2	0	0	4	7
3	0	0	2	4
4	0	0	1	2
Total -->	0	0	9	17



Reduced Sn has higher values of RRR, however, this value drops significantly between 10 and 20%.

Standard Sn values for RRR are mostly preserved from 0 to 10%.

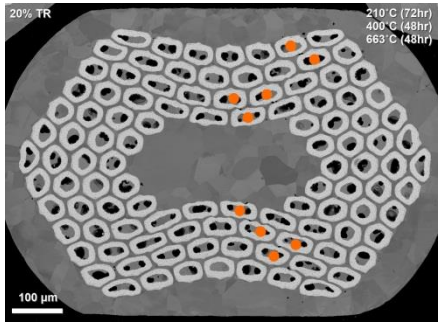
DB Leakage - Corner Filaments are not the problem!

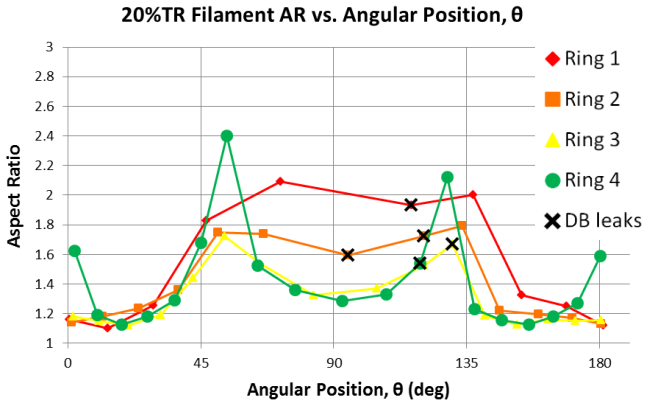
14982	Thickness Reduction			
Ring	0%	10%	20%	30%
1	0	0	2	4
2	0	0	4	7
3	0	0	2	4
4	0	0	1	2
Total -->	0	0	9	17

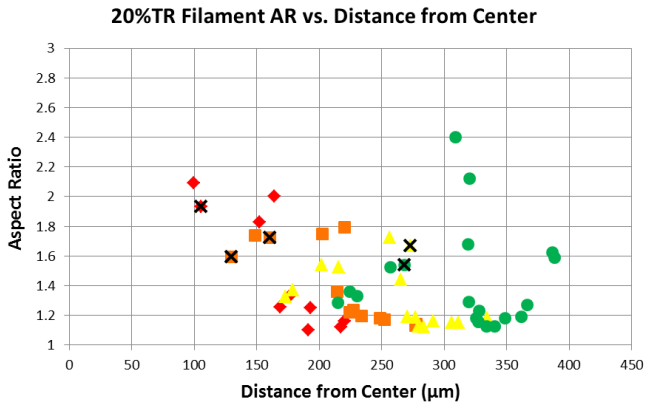
→ Note that it is not the outer corner filaments that are leaking, but the inner filaments.

→ If Sn leakage is to be affected significantly, support must be given to the inner filaments.

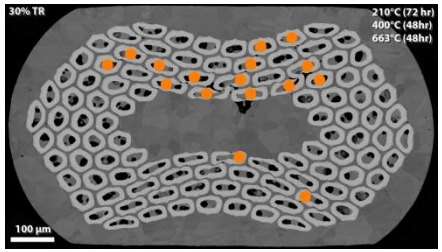
20% TR

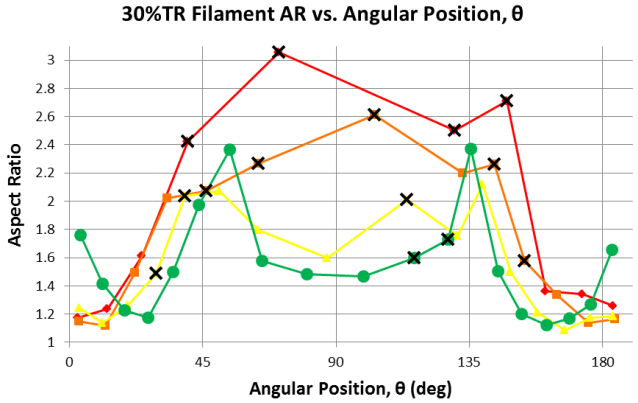


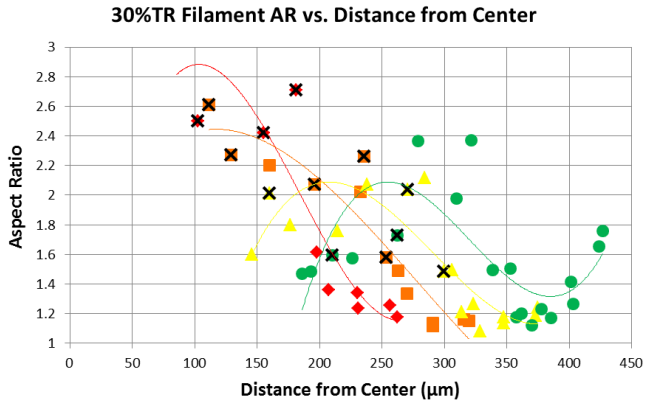




30% TR







Concluding Remarks – Hex Corner Filaments

Total fraction of hex corner filaments leaking

→ 6 per cross section → 4 cross sections per sample → 4 samples → 96 total corner filaments observed

→ Only 3 leaks from **corner filaments** → **only 3.1% total rate of leakage**

Inner ring filaments become the most heavily distorted as deformation increases leading to diffusion barrier failure.

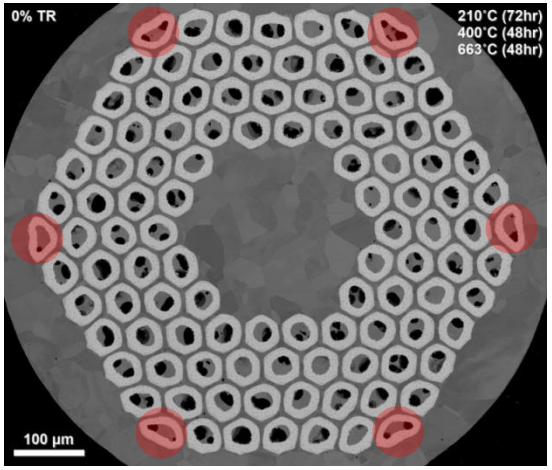
→ Rings 1 and 2 make up 23 filaments in each cross section → 4 cross sections per sample → 4 samples → 368 total filaments observed in Rings 1 and 2

→ 62 leaks from filaments in **Rings 1 and 2** → **16.8 % rate of leakage**

→ All but 3 of these leaks happen after 20% TR for inner rings → **DB leakage rates for inner two rings go from 0.8% (@ 10%TR) to 4.3% (@20%TR), then to 16.8% (@30% TR)**

What does this mean?

We should be worried about inner filaments, not hex corners.



Q & A