Microstructural Sources of Reduced Residual-Resistance Ratio in Nb_3Sn Wires

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Abstract

Residual resistance ratio (RRR) is a measure of metallic purity. In a superconductor inside a magnet system, impurities degrade the ability of electrical stabilizing materials to safely carry electric current in the event of a magnet quench. In this study, we have analyzed the ability of superconductor manufacturers to produce high-RRR niobium-tin (Nb_3Sn) wires in large batches and over time, as their productions have scaled up to meet current demand. Additionally, we have performed a microstructural investigation (using SEM/EDS) to determine the reasons for reduced RRR from one manufacturer. Nb_3Sn composite wires have never been produced in large quantities until very recently, and have never been characterized thoroughly. If statistical analysis shows that high RRR wire can be produced consistently, engineers will be capable of producing designs with an assurance that a batch of wire will behave as expected. Our microstructural analysis revealed that breakages within the diffusion barrier cause severe drops in RRR in the Nb_3Sn wires, a problem which can be remedied at the manufacturing level to result in more consistent wire.

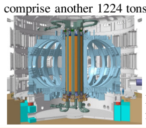
Experimental Approach

- Studied large manufacturing data sets of RRR variation with time to assess typical variation that occurs in this first-ever large production of Nb_3Sn.
- Examined wires with high RRR and low RRR to establish mechanisms for RRR degradation

Scale of Manufacture

In the table below (ref. 5) are listed the lengths and weights of the Nb_3Sn components in the ITER fusion reactor. This is the first commercial-scale manufacture of Nb_3Sn, and will involve 8 manufacturers on 3 continents. The NbTi components comprise another 1224 tons.

Coil	Superconducting Strand Weight (tons)	Jacket Weight (tons)
Toroidal Field	384	185
Central Solenoid	122	530



Pictured – The ITER fusion reactor

Effects of Heat Treatment on RRR

Typically, heat treatment takes place around 650 degrees Celsius. The longer a wire spends at that temperature, the more Nb_3Sn forms to yield a higher critical current density. However, the heat treatment can also decrease RRR as Cr or Sn impurities diffuse into the stabilizing Cu layer.

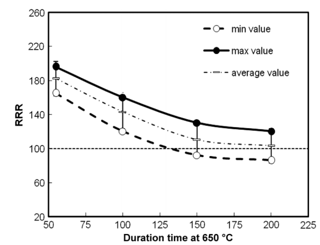


Figure 2.1 –As time at 650 degrees Celsius increases, Cr from the diffusion barrier leaks into the outer Cu jacket **(ref. 1)**

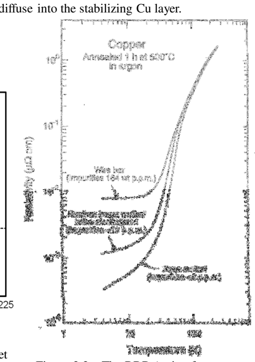


Figure 2.2 – The RRR (ratio of resistance at room temp to resistance at 0K) decreases as impurities increase. **(ref. 3)**

Effect of Mechanical Deformation on RRR

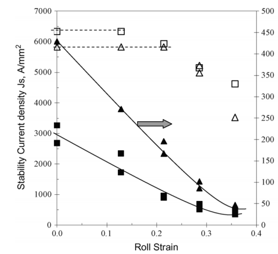


Figure 3.1 – RRR and J_c vs. strain
In general, as fractures occur in the diffusion barrier, Sn from the inner core of the wire leaks into the stabilizing Cu jacket, reducing its purity. **(ref. 4)**

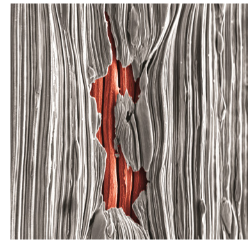
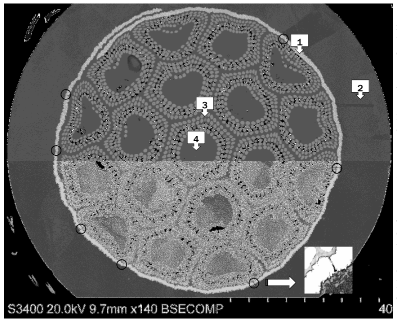


Figure 3.2 - A fracture in the diffusion barrier, in red (false-colored) are exposed Nb_3Sn filaments



Pictured in Figure 3.3 is a reacted Nb_3Sn wire in an internal tin configuration. Each wire consists of:

1) A chromium distribution barrier.

2) A stabilizing copper layer outside.

3) Bundles of Nb_3Sn filaments (which before reaction were bundles of niobium Filaments surrounding a tin core.)

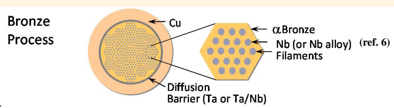
4) An inner copper matrix (Now occupying the space the tin core used to be.)

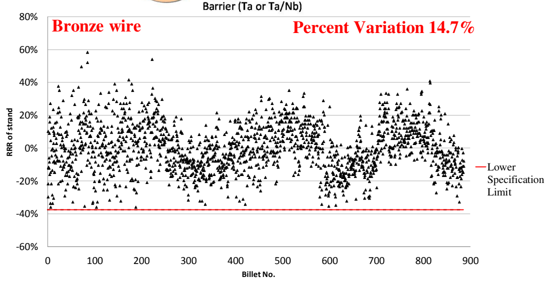
Circled: Fractures in the Diffusion Barrier (There were 13 counted at high magnification)

Figure 3.3 – A wire measured at a RRR of 17. Fractures resulted in a .31-.37% Sn impurity.

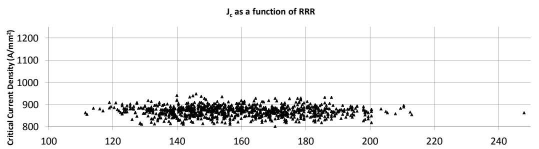
RRR	17	38	39	42	111	113	114	118	149	152	157	158
Breakages Counted	13	5	6	3	2	0	1	1	0	0	0	0

RRR Variance During Wire Manufacturing

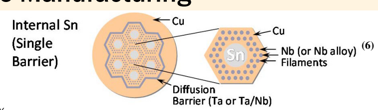


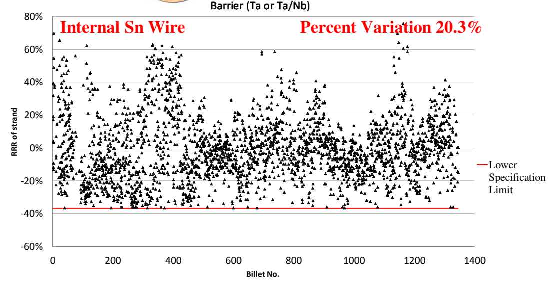


Across large productions (~1000 billets), RRR values exhibit a coefficient of variation (σ/μ) of 14.7%. In general (see figures 3.2 and 3.4), if J_c increases as RRR decreases, the RRR drops are a result of heat treatment. If J_c decreases as RRR decreases, mechanical stresses are the cause of RRR drops.

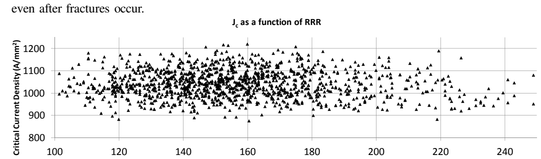


This plot plots J_c vs RRR for the manufacturer above. It shows no relationship between them, inferring that the manufacturer is not inducing the wires to excessive stresses, or heat treating the wire to excess.





Across large productions (~1000 billets), RRR values exhibit as coefficient of variation (σ/μ) of 20.3%, 32 percent higher than the bronze-processed wire. In a bronze process wire, the Sn must diffuse from the bronze into the Nb filaments; the Sn is less inclined to burst from the diffusion barrier even after fractures occur.



This manufacturer has greater variance than the bronze process Manufacturer. There is no significant relationship to demonstrate excessive stress or heat treatment.

Discussion of Results

- We have demonstrated the microstructural origin (diffusion barrier breakage) of low RRR in these commercial Nb_3Sn wires.
- The variance in manufacturing RRR (on left) suggest that the manufacturers are consistently heat treating the wire, but that non-uniform mechanical deformations are causing diffusion barrier breakages and RRR drop.
- Suitable RRR values are associated with an unbroken (or nearly unbroken) barrier.
- Bronze process wires present fewer difficulties in consistent manufacturing.

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