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J. Seuntjens
F. Clark
M. Erdmann
E. Coleman
B. Jones

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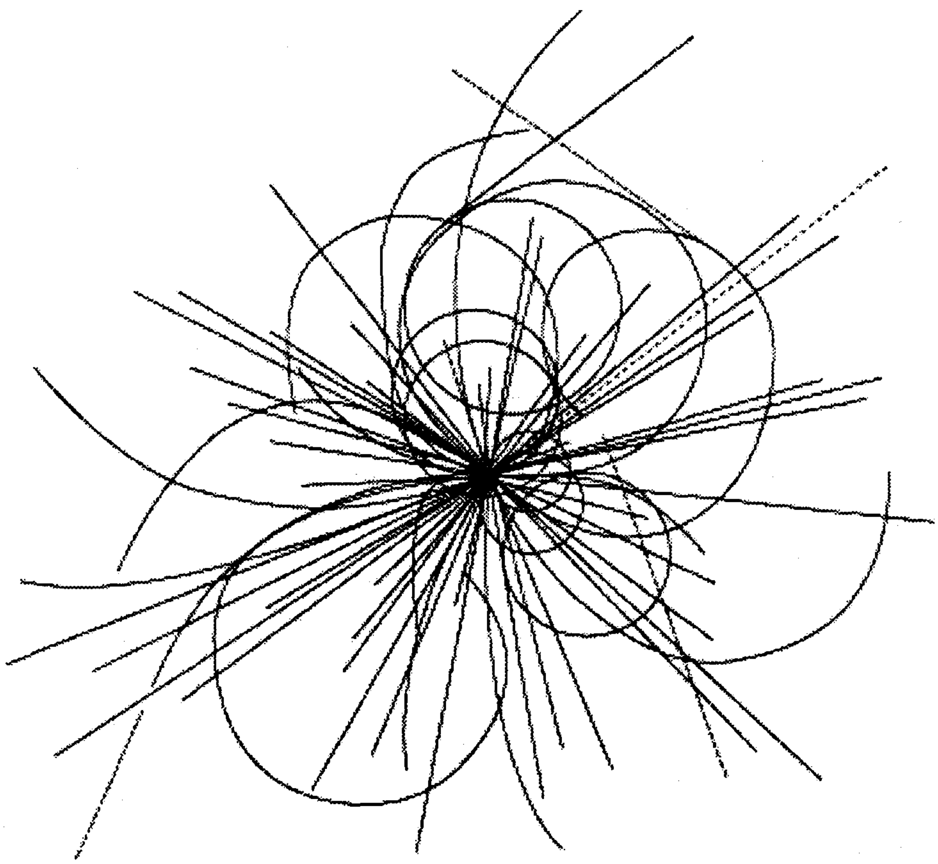

Superconducting Super Collider Laboratory

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Comparisons of Processes and Performance of SSC-VQP Material*

J. Seuntjens, F. Clark, M. Erdmann, E. Coleman, and B. Jones

Superconducting Super Collider Laboratory†
2550 Beckleymeade Ave.
Dallas, TX 75237

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COMPARISONS OF PROCESSES AND PERFORMANCE OF SSC-VQP MATERIAL

J. M. Seuntjens, F. Y. Clark, M. J. Erdmann, E. S. Coleman, and B. A. Jones

Superconducting Super Collider Laboratory*
2550 Beckleymeade Avenue
Dallas, TX 75237-3997

INTRODUCTION

The Superconducting Super Collider's (SSC) cable Vendor Qualification Program (VQP) will end in FY 1993. At the time of this writing, all 8 vendors involved in this program have demonstrated capability to fabricate conductor which meets SSC specifications. The magnet vendors have hard choices to make in calendar year 1993 in deciding which cable vendors will make the production cable. It is well accepted that because of requirements of magnet uniformity, that only one vendor will be chosen for dipole Inner cable, one vendor for dipole Outer cable, and one vendor for quadrupole Outer cable. The production quantities are nominally 500, 500, and 200 metric tonnes, respectively. Among the many deciding factors are a technically sound production process, process control, and production quantity capability of each cable vendor. Qualified vendors will have proven their technical process and process control is adequate for production quantities. This paper is part of ongoing effort to provide technical information for the magnet vendor's decision making process. Some of the Phase IB process data is summarized and well as results of a portion of the materials characterization performed at the SSC Laboratory. Key process and final product parameters for each cable vendor are compared without identifying specific vendor's process detail.

VARIATIONS BETWEEN STRAND PROCESSES AND FINAL STRAND PROPERTIES

All 8 vendors in the VQP use a common double extrusion process. A monofilament with 4 % nominal diffusion barrier is assembled, extruded, drawn, cut to hexagonal elements, and stacked into a multifilament billet. The multifilament billet is extruded, rod drawn, given 3-4 heat treatments with intermediate strains, and drawn to final size. At this time, all vendors are using a common NbTi alloy source as well as OFHC copper for their raw materials. Raw material differences have been presented earlier. [1] Since each qualified vendor's material meets SSC specifications, the most relevant technical issue is to identify differences between each vendor's materials.

Key process parameters are recorded for each billet produced in the VQP. This data has been taken from the SSC-VQP database[2] and averaged for each vendor's phase IB production. Table 1 below lists the minimum and maximum average Phase IB values for key parameters in the double extrusion processes. Monofilament processes vary widely. However, the parameters near the end of the process tend to have less variation. All strand processes attempt to provide adequate superconducting properties and maximize mechanical robustness., which explains some of the similarities near the end of the process.

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Characterization of monofilament from the Phase IB processes has been presented earlier.[3] The final strand properties are given in table 2 for each cable vendor. The Ic, Jc, and RRR are as reported from the vendor. The slope was measured at the SSCL between 5.6 T and 7 T for Outer and 7 T and 8 T for Inner. The r/D, final strand tensile strength, and springback measured at SSCL is also presented for comparison. In each case, the average value from Phase IB is reported. The properties of the cables made from this strand are discussed elsewhere in these proceedings.[4]

Table 1. Key strand process parameters and the minimum and maximum Phase IB average values reported in different vendor's processes.

Parameter	Min	Max
Nb barrier fraction (% of filament)	3.8	4.3
Virgin copper RRR	180	380
Mono. billet aspect ratio	2.6	6.3
Mono. extrusion temp. (^oC)	240	810
Mono. extrusion reduction ratio	9.7	92
Mono. restack diameter (mm)	1.8	3.3
Multi. theoretical yield (km)	62	223
Multi. Billet aspect ratio	2.2	5.7
Multi HIP temp. (^oC)	25	580
Multi. extrusion temp. (^oC)	500	650
Multi. extrusion reduction ratio	6.3	17
Last heat treatment temperature (^oC)	375	405
Number of heat treatments	3	4
Heat treatment total time (hours)	160	320
Final drawing strain	3.9	4.6

Table 2. Phase IB averages for final strand properties for each vendor.

Vendor	Ic (A)	Jc (A/mm^2)	Slope (A/mm^2 T)	RRR (final)	r/D	Tensile, final (MPa)	Springback (degrees)
AISA	289	2484	550	187	0.113	849	875
OTU	316	2689	600	209	0.098	856	850
FEC	293	2438	606	108	0.095	875	925
HIT	300	2431	539	157	0.108	860	780
OST	305	2568	550	222	0.131	835	760
IGC	383	1736	530	181	0.087	937	854
TSC	387	1737	596	139	0.096	855	837
SEI	374	1649	511	135	0.092	949	825

The tensile strengths are similar for all Inner and all Outer cable vendors. If we average the similar vendor's numbers we get 914 MPa for Inner (56.5 % copper) and 855 MPa for Outer (64.3 % copper). Smith[5] reports a tensile strength of approximately 60 ksi (414 MPa) for fully cold worked copper. If one places these 3 data points on a common plot of tensile strength vs. % copper, one can predict the tensile strength of 6 μm NbTi filaments. The plot in figure 1 shows good correlation and a predicted NbTi tensile strength of 1595 MPa at the Y intercept. In earlier work sponsored by SSCL, Liu[6] reported that NbTi filaments have a tensile strength of 195 ksi (1334 MPa) at a filament size of 260 μm. This suggests that in these composites with high strain, the rule of mixtures is obeyed. Also included in figure 1 is an average tensile strength for the restack monofilaments of 920 MPa and 665 MPa for bare NbTi and copper clad monofilament, respectively, reported earlier for cases without monofilament anneal.[7] The monofilament has no precipitation and far less cold work and clearly does not fall on the line representing the extreme cold worked condition.

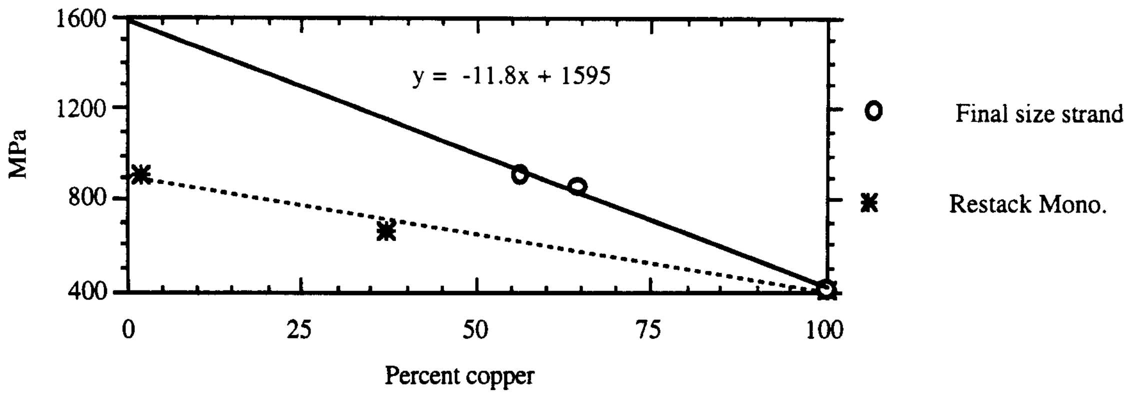

Figure 1 . (Upper) Tensile strength vs. % copper for pure copper, the average Inner and the average Outer strand values. A linear extrapolation for 6 μm NbTi filaments is 1595 MPa. (Lower) Tensile strength of bare NbTi and copper clad monofilaments at restack. Bare NbTi is shown slightly off set from the Y axis.

A series of image analysis measurements on a select series of samples from the each vendor's program have been made. The filament roundness and filament area coefficient of variation (CV) have bee measured on 3-5 billet's samples from each vendor. This data is intended to present typical values for the vendor. In any one vendor, the number of samples are too small to yield statistical information. The techniques used in these measurements have been discussed in detail elsewhere.[7]

Figure 2 plots the filament area CV after first and last heat treatment as well as final size. The data after first heat treatment is incomplete at this time. Figure 3 displays the filament roundness for each vendor's material at monofilament restack, previously reported[7], as well as after first heat treatment, after last heat treatment, and final size strand.

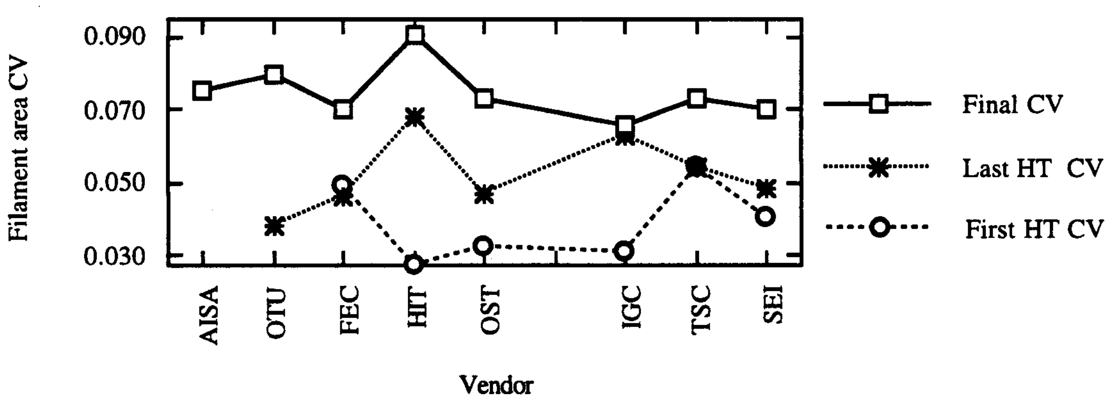

Figure 2. Filament area CV for each vendor after first and last heat treatment as well as final size strand. The data after first heat treatment is incomplete at this time.

DISCUSSION

The Phase IB monofilament billet design and process parameters vary widely. The multifilament billets also vary widely in aspect ratio and theoretical yield. However, their extrusion temperatures and extrusion reduction ratios are considerably closer to each other than the monofilament billets. The variation in the multifilament heat treatment temperature and total heat treatment time are reflected in the 9 % range for Ic between the vendors shown in table 2. The final strain varies by no more than 40 % (approximately 2 drawing die passes) for all of the vendors.

The slope of the Jc vs. field has a range of about 20 % between vendors and does not correlate to other process parameters. The final RRR is on the order of 60 % of the raw copper value. The RRR annealing procedures were not identical for each vendor in Phase I. The r/D of the Inner composites is similar. OST material has significantly different r/D than all other Outer vendors.

The tensile data for Inner and Outer strand, combined with cold worked copper data, indicate that these composites have little deviation in strength from the rule of mixtures. The calculated tensile strength of 6 μm filaments is approximately 1600 MPa. The monofilament data also follow the rule of mixtures, however the cold worked (strain of >3) NbTi tensile strength, in the absence of precipitation heat treatment, is 920 MPa.

The filament area CV is typically 3-4 % after first heat treatment, 4-7 % after the last heat treatment, and 7 to 9 % at final size. The data indicate that the filament "sausaging" occurs gradually throughout the multifilament process. The roundness data show that the filaments distort between the monofilament restack and first heat treatment, falling from 0.82 to 0.72, respectively. The roundness does not appear to further degrade during the heat treating and drawing strain as does the filament area CV. Note that the filaments with the highest degree of roundness also have the highest filament area CV. Distortion of the filaments is most noticeable to the eye and is undesirable because it increases the filament perimeter which reduces the barrier thickness. In the present case of adequate barriers for all vendors, distortion is not a serious problem because it is not generally severe enough to "puncture" the barrier or allow electrical "bridging" of filaments. Sausaging is less noticeable to the eye and is thought to be more troublesome in that it reduces the composite Ic. These result suggest that filament distortion and filament sausaging are separate phenomena.

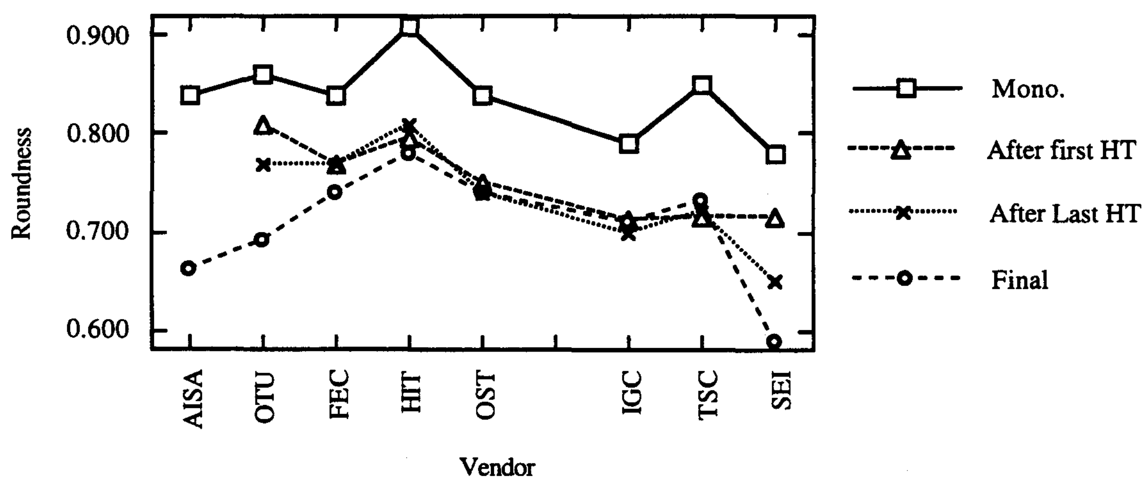

Figure 3. Filament roundness for each vendor at monofilament restack, after first heat treatment, after last heat treatment, and final size strand. A roundness value of unity represents a filament with a circular cross section.

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