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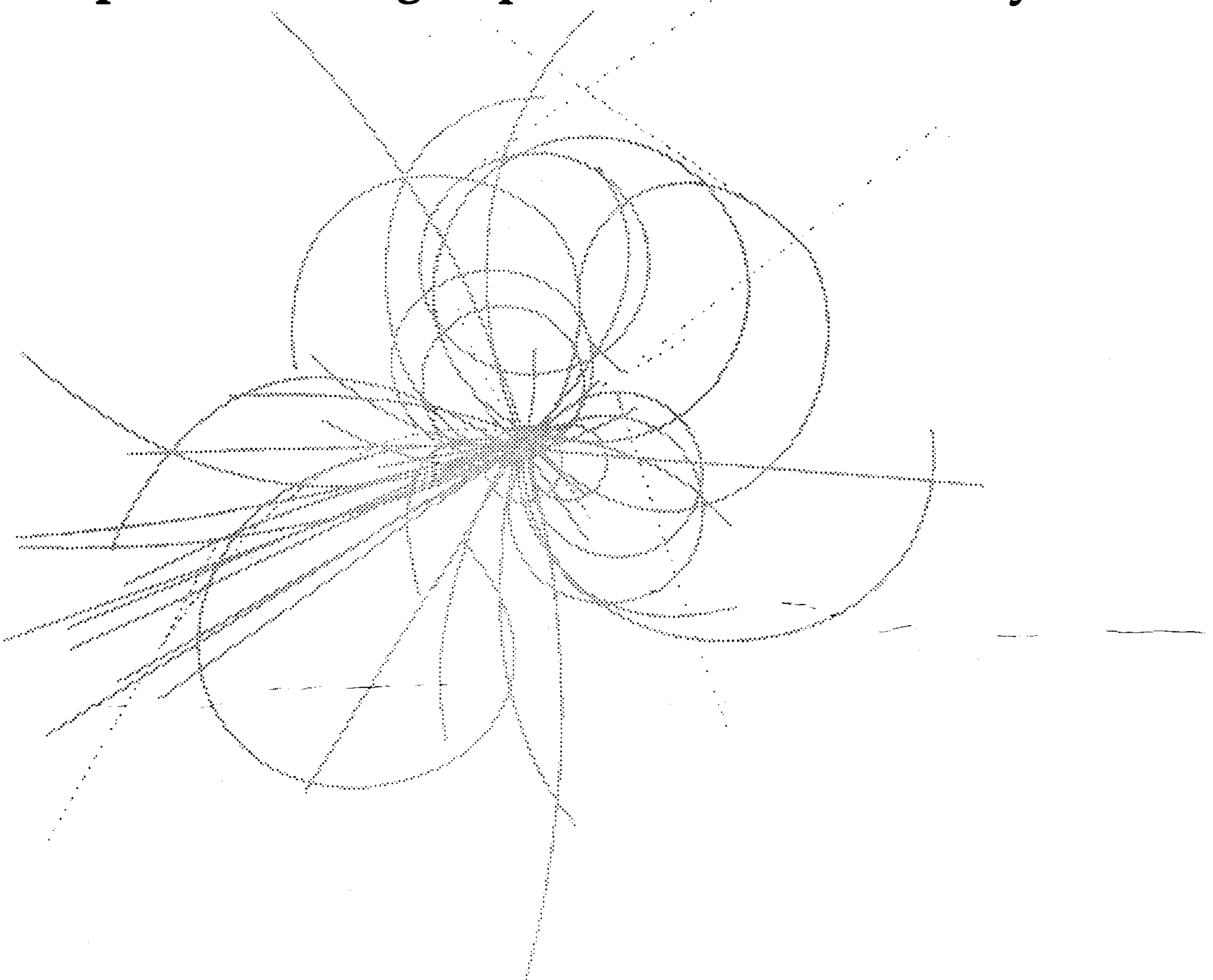

Filament and Critical Current Degradations in Extracted Strands of SSC Cable

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FILAMENT AND CRITICAL CURRENT DEGRADATIONS IN EXTRACTED STRANDS OF SSC CABLE

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Abstract: Previous work by Goodrich et al. have shown that virtually all of the voltage in a strand of cable at I_c is concentrated locally at the edges where the damage is severest. We have worked to characterize this local degradation both microstructurally and electromagnetically. Scanning electron microscopy and image analysis have been used to characterize filament defects and uniformity throughout the edge and flat regions of the strand. A summary of this work is given and is correlated to recent electromagnetic results on the distribution of critical currents along the strand.

INTRODUCTION

Rutherford-type cables used for SSC magnets typically suffer a 5 to 10% loss in critical current over the sums of the critical currents of the strands that comprise the cable. The reported amount of degradation is usually quoted between -2 and +5% because a self field correction is used for the cable I_c, but is rarely used for strand measurements. Understanding the nature of the degradation will minimize the degradation and will directly increase the operating margin of accelerator magnets. Previous work by Goodrich and Bray[1] has shown that virtually all of the voltage, at I_c, across an extracted strand from a cable is localized at the narrow and wide edges of the cable. Therefore, it is apparent that the degradation is not uniform throughout the strand. We have attempted to characterize the nonuniformity of

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filaments along extracted strands of cable as well as the distributions in critical currents. Our early results are presented in this work.

EXPERIMENTAL

A 40 mm outer cable, No. SSC-O-S-00015, was studied in this work. The strand from this cable was made at Supercon, Inc., (billet No. 2071). The reported cabling degradation for this cable was 10.3%. This value is typical for 40 mm cables and compares to 2% for current 50 mm cable production. After the winding, the cable was cut about 1 m from the cabling machine turks-head, the turks-head was opened up, and the cable was backed through the turks-head. The strands were then cut at the spools and labeled. The section of the cable with its virgin strands was removed intact. The cable was dismantled with minimal plastic deformation providing continuous samples of virgin and extracted strand. This procedure allowed for unambiguous identification of each strand by referencing the re-spooling map for the cable.

Metallurgical mounts were made of the virgin strand and of the sections of the extracted strand from the narrow edge, wide edge, and face of the cable. A sharp bend specimen made from a section of virgin strand was also mounted for comparison. Care was taken to ensure that the sections were normal to the wire axis at the section. A sharp bend section of virgin Sample 6 was made to give an extreme case for strand distortion. A section was made normal to the strand axis in the middle of the bend. A JOEL 6100 SEM with a Link Analytical eXL image analysis system was used to determine the relative cross sections of filaments from each section. Specimens were analyzed as polished, with no surface relief of the filaments. Backscatter imaging was found to have insufficient resolution, and the large back-scatter signal from the Nb-Ti filaments made them appear artificially large. All images analyzed were thus created using a 25 KeV primary beam with secondary electron imaging at 750×. Approximately 50 frames were averaged to give the best resolution image. Each filament contained approximately 300–650 pixels to give an accurate filament representation. Approximately 200–300 filaments were analyzed in each image, and 4–5 images were obtained for each sample.

Virgin and extracted strands had their critical current and current distributions measured at Oregon State University. Brass sample holders were used which allowed extended transitions to be measured to several hundred microvolts without excessive heating. The current carried by the barrel was determined from independent tests as a function of field and voltage and was then subtracted from the total current. (It was assumed that the barrel is simply a parallel circuit.) Stable, reproducible, and non-hysteretic currents were measured to the point where voltage was proportional to current (i.e., $V \alpha I^n$, where $n = 1$ and no additional super current exists). Measured samples were 30 cm long; in the extracted strand case, this results in the sample having two cable wide edges and two cable narrow edges. Details of the critical current distribution work will be published elsewhere.[2]

RESULTS

Microstructural Uniformity

Two strands of this cable (Nos. 6 and 7) were analyzed in this work. They had reported diameters of 0.0255 in. (0.648 mm) and copper to superconductor ratios (Cu:SC) of 1.71 and 1.67 to 1, respectively. Figure 1 contains schematic cross sections of the virgin, sharp bend, cable broad face, cable wide edge, and cable narrow edge sections of No. 6 traced from photomicrographs. Significant distortion of the filament array can be seen as compared to the bull's-eye-like pattern of the virgin strand. In general, however, the filaments adjust themselves within the array, and little distortion can be seen at the filament level.

A plot of the frequency vs. gray level is made from the stored image during the image analysis. A typical plot is shown in Figure 2, where two distinct peaks are shown, one for the filaments and one for the matrix. A gray level is chosen at the minimum between the two peaks to define the boundary between the filaments (shaded) and the matrix. A binary image is then created with all pixels with gray level below the boundary set to be black to represent the filaments. All remaining pixels are set to white to define the matrix. A representative binary image is shown in Figure 3. The number of filaments in this image is restricted to only about 200 for clear journal reproduction. A variety of statistical analyses are then performed on the filaments, and the pixel statistics are reported here.

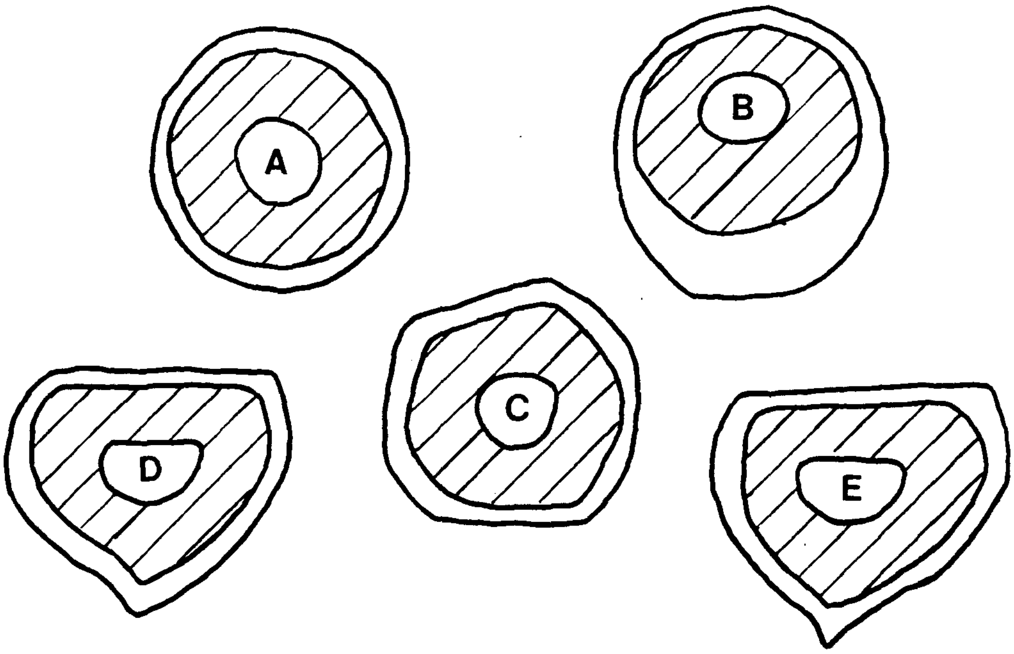

Figure 1. Schematic cross sections of samples in this study showing the strand cross section with filament array shaded. A) virgin strand, B) sharp-bend, C) cable broad face, D) cable wide edge, and E) cable narrow edge.

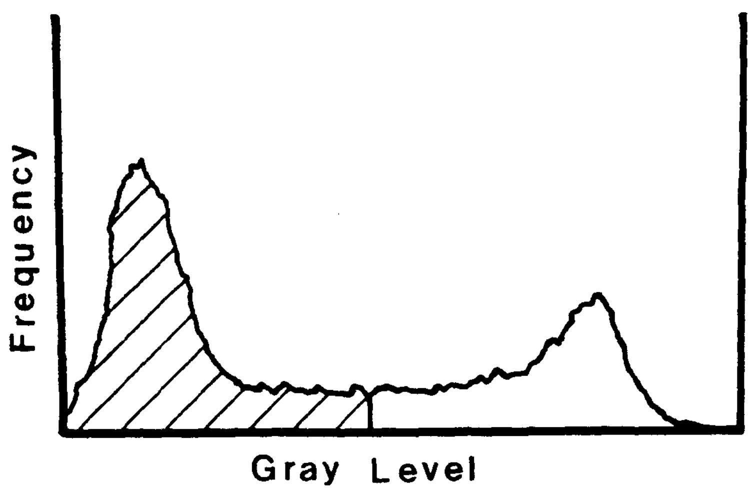

Figure 2. A plot of frequency vs. gray level from a stored image. The minimum in the curve defines the border between the filaments (shaded) and the matrix.

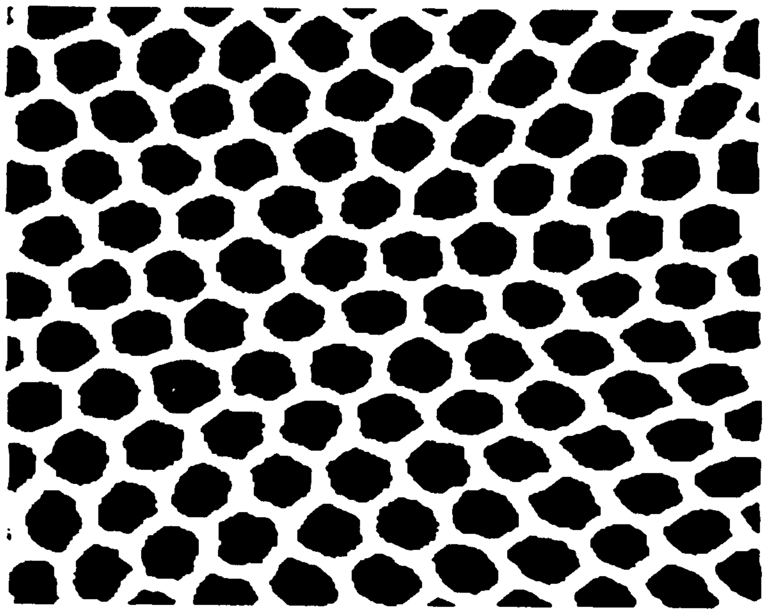

Figure 3. Binary image made from the defined distribution in Figure 2. Only ~200 filaments are shown for clear journal reproduction.

Table 1 contains the data from this study, with values from an ideal 6 µm Outer conductor given in the first row. Samples are identified by the following letters: V = virgin strand, VS = virgin sharp-bend, F = cable broad face, W = cable wide edge, and N = cable narrow edge. The Min, Mean, and Max columns are the filament cross-section values (in μm^2). Area (SC) is the area of the superconductor (in mm^2) calculated from multiplying the mean filament cross-section by 4173, the number of filaments in an ideal outer conductor. Area (sample) is the measured cross-section of the given section (in mm^2) with the virgin strand calibrated to match the measured 0.0255 in. (0.648 mm) diameter. The Cu:SC ratio is calculated from the Area (SC) and Area (sample) data.

Table 1. Virgin and Cabled Strand Data.

Sample	N	Min	Mean	Max	Std. Dev. (%)	Area (S/C)	Area (Sample)	Cu:SC ratio
(IDEAL)	4173	*	28	*	*	0.118	0.33	1.80
6V	515	20	28	35	9	0.118	0.33	1.80
6VS	1400	13	32	126	57	0.135	0.398	1.95
6F	924	21	29	40	9	0.119	0.329	1.76
6W	1257	21	28	35	8	0.116	0.317	1.73
6N	959	22	27	40	10	0.112	0.309	1.76
7V	585	23	29	38	7	0.122	0.345	1.81
7F	825	22	30	38	8	0.124	0.337	1.72
7W	756	20	29	34	8	0.120	0.337	1.72
7N	944	23	28	37	10	0.118	0.317	1.69

Approximately 12% of the filaments in the virgin strand were surveyed. The mean filament size matches the ideal value of 28 μm^2 for virgin strand No. 6. Thus, the area of superconductor also matches the ideal value, and since the diameter of the strand was measured to be 0.0255, we have calibrated the sample area to be 0.330 mm^2. The Cu:SC ratio is thus 1.80:1, which is slightly higher than the measured value of 1.71:1. In comparison, the sharp bend sample has a larger mean filament size and measured strand cross section. The inside of the bend is at the bottom of "B" in Figure 1, and it can be seen that locally the Cu:SC ratio is increased. The measured value of 1.95:1 is consistent with this observation. The most noteworthy observation is the extreme range of filament cross sections in the sharp-bend. The minimum filament size is almost a factor of 10 smaller than the largest filament size, and the standard deviation of 57% in the sharp-bend is about 6 times higher than the virgin strand standard deviation of 9%.

Approximately 20-30% of the filaments in the extracted strand sections were surveyed. An interesting result in the strands extracted from the cable is that the standard deviation (sigma) in percent increases only slightly from the virgin strand. In fact, if the sigma is expressed in μm^2, rather than in percent, there is no significant difference in sigma between virgin and extracted strands. This result suggests that despite the deformation of the filament array, the filament uniformity is not degraded by the cabling process.

It can be seen from Figure 1 that as one proceeds from the virgin strand to the broad face to the wide edge to the narrow edge, the strand cross section is progressively more distorted. The measured cross section of the strand decreases as the distortion increases. The narrow edge cross section of the the extracted strand is about 6% smaller than the virgin strand. In addition, the mean filament size also decreases accordingly with the decreasing strand cross section. The narrow edge section is again the extreme case where the filament cross section is about 5% smaller than the virgin section. Since the filament and the strand cross section both decrease concurrently, the calculated Cu:SC ratio does not change greatly. However, a weak trend is seen where lower Cu:SC ratios occur for the more distorted, smaller cross-section sections.

Strand No. 7 was measured in a manner similar to No. 6 to test the consistency of this work. In general, the same trends are seen as in strand No. 6. The Cu:SC ratios tend to be lower than strand No. 6, which reflects the lower reported value of 1.67 from the vendor. As in strand No. 6, the mean filament cross section and strand cross sections also decrease as the strand distortion increases. However, all values for strand No. 7 are slightly larger than the strand No. 6 counterparts, suggesting that virgin strand No. 7 is larger than strand No. 6, despite the fact that the measured virgin strand diameters are identical for both strands.

Critical Current Distributions

The second derivative of the V vs. I plot gives the critical current distribution in the strand. Figure 2 contains distributions from virgin and cabled strand No. 10. The I_c is 306 and 296 A, respectively. The distributions are about 10 A wide or about 3% of I_c for both the virgin and extracted strand samples. The peak in the distribution for the extracted strand is about 8 A lower in current than the virgin strand, in agreement with the lower I_c result.

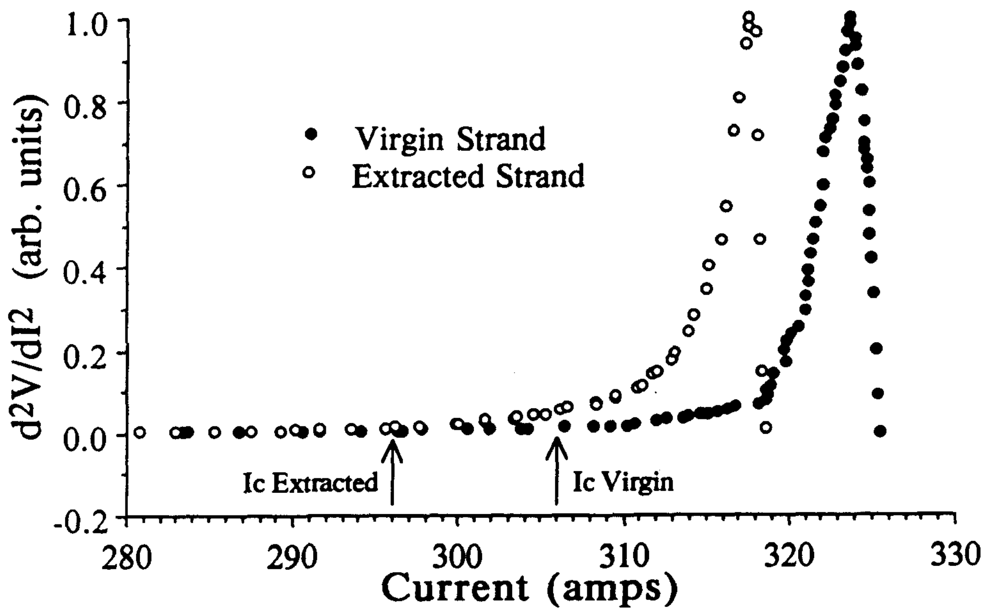

Figure 4. Second derivative of V vs. I data on strand No. 10. Virgin strand (top) and extracted strand (bottom). I_c (10^{-14} Ωm) for the virgin and extracted strands are shown.

DISCUSSION

It is thought that significant filament distortion would induce "sausaging" of the filaments, where the cross section of the filament changes along its length. As described in a model by Warnes,[3] current transfer can take place between sympathetic sausaged filaments. However, this transfer is a resistive link; thus significant sausaging reduces I_c as compared to unsausaged filaments. It is expected that increased sausaging would be apparent as an increase in the filament cross-sectional area standard deviation. The unchanging standard deviation observed suggests that the cable degradation is not strongly related to filament sausaging.

It is known that most of the cabling degradation is located at the wide and narrow regions of the cable.[1] These results show that these regions have a cross section reduced as much as 6% compared to the virgin strand and the face of the cable. This locally reduced cross section will then have a corresponding decrease in I_c due to the smaller superconducting material cross section. I_c may be further decreased by a possible reduction in J_c associated with the additional strain in the edge region; however, even at a strain of 6% (ε=0.1), this is not large enough to reduce J_c significantly.

Since it is difficult to survey all filaments without repetition, operator judgement is used to select representative regions for examination. However, the lack of change in the filament cross section σ suggests that any section chosen is representative. The validity of this image analysis technique requires more verification. Future work will be performed on extracted strands of 50 mm cable to determine whether the amount of cross section reduction is significantly less than with 40 mm cable, as predicted by the greatly reduced cabling degradation in 50 mm cable designs.

The critical current distributions indicate that the filament deformations due to cabling are both small and localized. If the deformations were uniformly distributed along the strand length, the distribution in I_c would broaden on cabling. The similarities between the virgin and extracted strand I_c distributions show that this is not the case. In addition, since the distribution apparently has been shifted to lower currents in the extracted strand, the deformation is occurring locally and is uniformly lowering the I_c. This occurs mostly at the cable edges, where the distortion is greatest. The shift in the I_c distribution is only about 3%, which is in agreement with the measured change in the mean filament size at the narrow edge. The changes in critical current density and filament size are, however, near the measurement limits, so they should be treated with caution. The overall cable degradation was reported to be 10%, significantly higher than the drop in I_c for strand No. 10 described here. Work is underway to examine the remaining extracted strands in this cable using transition shape analysis.

ACKNOWLEDGEMENTS

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