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Strain and Magnetization Properties of High Subelement Count Tube-Type Nb_3Sn Strands

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***Abstract*—A tubular technique for economical production of Nb_3Sn material with large numbers of subelements is being explored by Supergenics I LLC and Hyper Tech Research Inc. The number of subelements was increased to 919 (744 subelements plus 175 Cu filaments) by increasing the size at which restacking is carried out. The product exhibited no fabrication problems and was drawn down and tested at a wire diameter of 0.42 mm, where the subelements are 10 μm in diameter. Recently we increased the subelement number to 1387 (1248 subelements plus 139 Cu filaments), which gives a subelement size of 12 μm in 0.7 mm diameter wires.**

Heat treatment (HT) of different subelement restacks has been investigated, and the best results of critical current and stability are presented. The strain tolerance of the strands with 192 and 744 subelements was also tested, and the strand with fine subelement size showed a high intrinsic irreversible strain limit.

***Index Terms*—Axial strain, irreversible strain limit, low loss, Nb_3Sn superconductor, tube approach.**

I. Introduction

THE two primary methods of making multifilamentary Nb_3Sn with high current density are the Internal-Tin (IT) process [1], and the Powder-in-Tube (PIT) [2] approach. The Bronze process [3], which yields a reliable and mechanically very strong product, typically has low current-current density (J_c) since Sn content in bronze is limited to less than 16 wt%. The IT approach with Sn confined by Nb or Nb alloy barriers still has the highest J_c [4], [5]. The J_c obtained with the PIT process has increased significantly in recent years [6].

Supergenics I LLC and Hyper Tech Research Inc. have explored several approaches including a tube approach [7]–[9]. In order to produce a strand that is stable over a wide field range, we have concentrated our research on lowering the effective filament diameter (d_{eff}). In this paper we describe some of our recent work on this tube approach that has been directed at producing strands with a large number of subelements in order to lower d_{eff}. We have previously reported [9] results on a 217-subelement strand. In this paper, we summarize our results on such strands and also give data on strands containing larger numbers of subelements. We also report the effects of axial strain and various heat treatments on J_c for the 217-subelement strand. Our present work has been on the feasibility of decreasing d_{eff} by increasing the number of subelements. We have made and examined some of the properties of wires containing 744 subelements.

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TABLE I
EFFECT OF HEAT TREATMENT TIME ON T1505 MATERIALS

PreHT at 575 °C	HT temperature	HT time	J_c at 12T/4.2K, A/mm^2
Yes	625 °C	700 h	2366
No	625 °C	500 h	2443
Yes	625 °C	300 h	2510

II. Results on Strands Containing 217 Subelements (192 Nb_3Sn Subelements and 25 Cu Subelements)

We have continued work on the T1505 strand previously reported [9] and, by modifying the heat treatment, we have been able to produce material with J_c of 2510 A/mm^2 at 12 T and 4.2 K in tests carried out at the Brookhaven National Laboratory (BNL). This is achieved by giving the sample a preheat treatment at 575°C for 48 h, followed by a heat treatment at 625°C for 300 h. The effect of reducing the heat treatment time at 625°C is shown in Table I. This reduction of the heat treatment period duration improves J_c values, possibly through limiting the grain growth. We performed fracture SEM of the two samples heat treated under 625°C for 300 h and 500 h, as shown in Fig. 1. Image tool was used to measure the average grain sizes in both pictures. There is no discernable difference between the two samples. The average grain size is 107 nm and 113 nm for the samples heat treated for 300 h and 500 h, respectively.

We measured the magnetization curve for T1505 strands after the heat treatment at 625°C for 300 h. The magnetization curve shows little flux jumping when the strand is cycled over the entire ±3 T field range (see Fig. 2). We sent the remaining strand to National Institute of Standard Technology (NIST) for strain sensitivity measurements by use of a CuBe Walters' spring apparatus [10]. The results of the tests at 12 T and 15 T are shown in Fig. 3. This strand has an intrinsic irreversible strain limit

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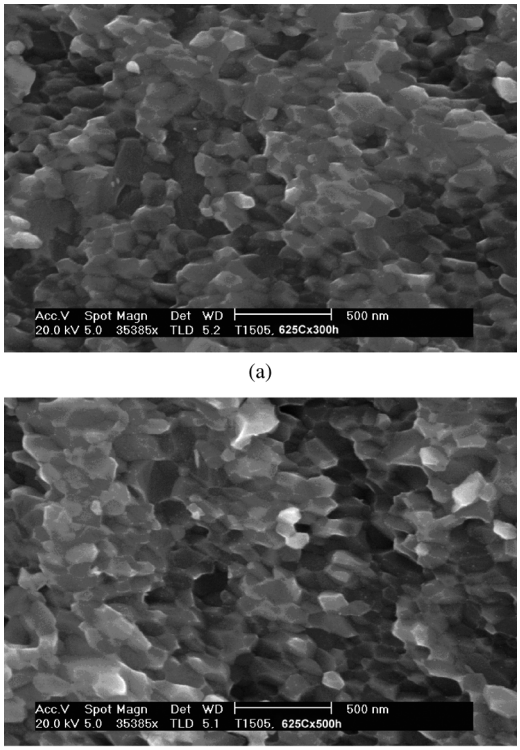


Fig. 1. SEM fractography of 0.7 mm diameter T1505 after different heat treatments. (a) 625°C for 300 h; (b) 625°C for 500 h.

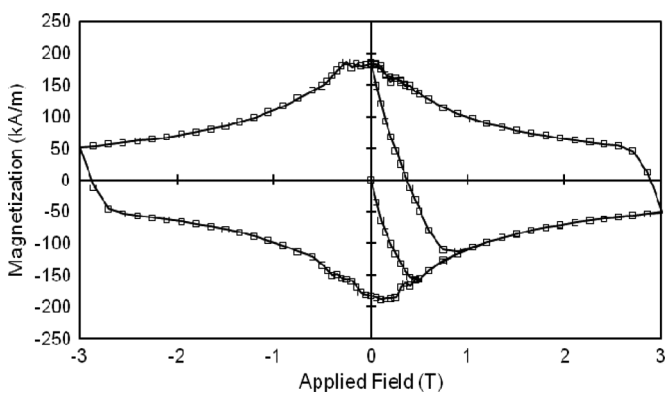


Fig. 2. Magnetization curve of strand T1505 with a subelement size of 36 μm.

$(\varepsilon_{irr,0})$ of about 0.23% on average, which is comparable to the PIT conductors [11] and regular Internal-Tin conductors [12].

III. Results on Strands With Low D_{eff} Arrays

In order to increase the number of subelements above 217, we increased the size of the tube used for the restack from 19 mm (3/4″) to 38.1 mm (1.5″) [7]. In an effort to reduce d_{eff} further, we made a 396 subelement restack, denoted as T1692. In this strand, with a 0.7 mm wire diameter, the subelement size was 21 μm. This assembly was drawn down to 0.42 mm where the filaments were 13 μm in diameter. Table II summarized all the billets mentioned in this paper. Fig. 4 shows the 0.7 mm strand after heat treatment at 625°C for 150 h, showing the subelement size of about 20 μm.

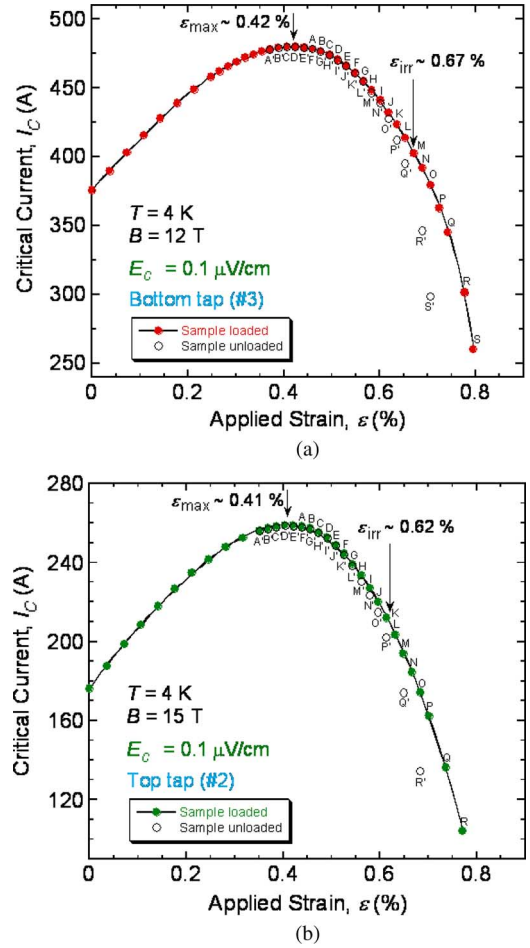


Fig. 3. Critical-current versus applied axial tensile strain measured on samples of strand T1505, heat-treated at 625°C for 300 h. The intrinsic irreversible strain limit $(\varepsilon \mathrm{irr}, 0 = \varepsilon \mathrm{irr} - \varepsilon \max)$ is about 0.23% on average. Measurements were made at 4.0 K and at (a) 12 T and (b) 15 T.

TABLE II
Billet Name and Related Subelement Size in Different

Billet Name	Subelement count	Subelement Size (μm) at 0.7 mm strand	Subelement Size (μm) at 0.42 mm strand
T1505	192	36	--
T1692	396	21	13
T1791	744	16	11
T1982	1248	12	--

Based on the successful reduction of this restack strand we decided to make a 744 subelement restack (T1791) where the subelement size at 0.7 mm wire diameter is 16 μm (Fig. 5). This assembly was drawn down to 0.45 mm where the filaments were 11 μm in diameter (Fig. 6). We heat treated the 0.7 mm T1791 strand at 625°C for 120 h and tested its non-Cu J_c at the Ohio State University (OSU). The heat treated strand gave a non-Cu J_c of 1939 $\mathrm{A/mm^2}$ at 12 T, 4.2 K. Fig. 7 shows the cross section of this wire after reaction, which indicates that the subelements were almost all fully reacted. Learning from the previous heat treatment of T1505, we reduced the heat treatment period to 100 h and prepared samples for strain sensitivity measurements at NIST.

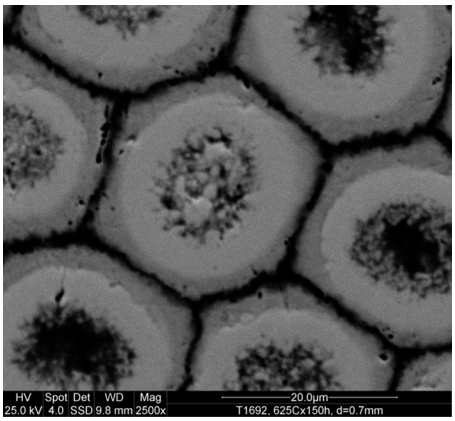
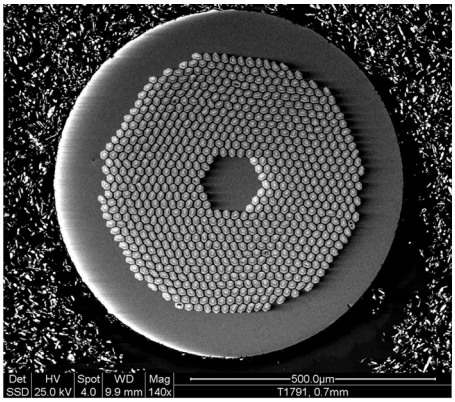
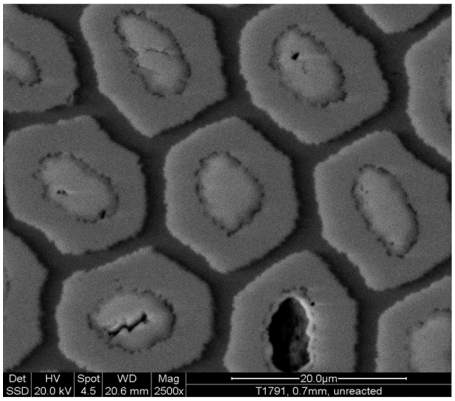


Fig. 4. Wire T1692 at 0.7 mm diameter after 150 h at 625°C.



(a)



(b)

Fig. 5. Cross-section of T1791 at 0.7 mm, 744 subelements. (a) T1791, 0.7 mm; (b) T1791, close-up.

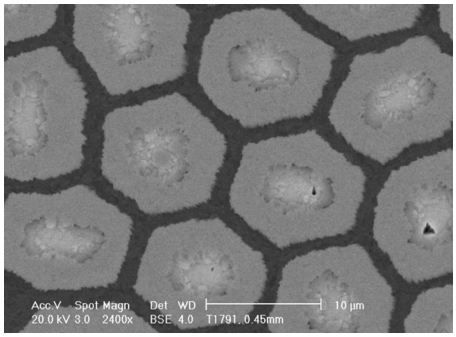


Fig. 6. Cross-section of T1791 at 0.45 mm, 744 subelements.

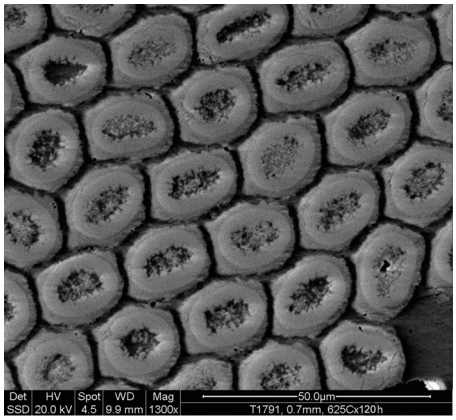


Fig. 7. T1791 at 0.7 mm diameter after 120 h at 625°C.

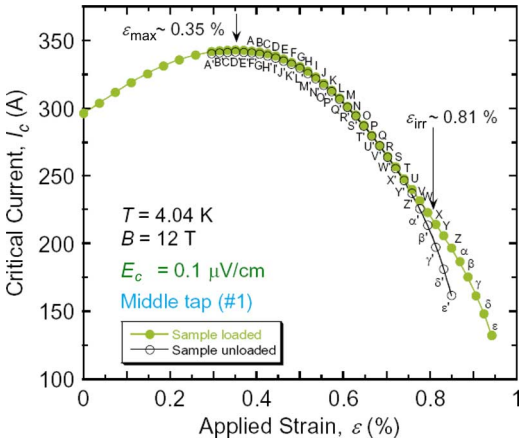


Fig. 8. Critical-current versus applied axial tensile strain measured on sample of strand T1791, heat-treated at 625°C for 100 h. The intrinsic irreversible strain limit $\varepsilon\mathrm{irr}, 0$ is about 0.45% on average, which is significantly better than that of T1505.

Two T1791 samples were measured for strain sensitivity and show similar properties. Fig. 8 shows critical-current versus applied tensile strain curve for one sample at 12 T. The average intrinsic irreversible strain limit of the two tested samples is about 0.45%. This relatively high value indicates that the tolerance of Nb_3Sn filaments to cracking under the influence of axial tensile strain is quite high in this wire. Compared to our 217-subelement restack strand T1505, $\varepsilon_{irr,0}$ of this 744-subelement wire (T1791) is significantly better than that of the 217-subelement (T1505). The two wires are similar except for the difference in the number of filaments, which leads to a filament size of 16 μm in the wire T1791 versus 36 μm in the wire T1505. This remarkable improvement in $\varepsilon_{irr,0}$ of wire T1791 is possibly due to its finer filaments.

Fig. 9 shows the magnetization curve of the 0.7 mm T1791 wire. The low non-Cu AC loss ($\sim$ 1200 $\mathrm{mJ/cm^3}$ for a $\pm$3 T field cycle) and the absence of flux jumps indicate that the filaments did not merge significantly during the heat treatment. Its

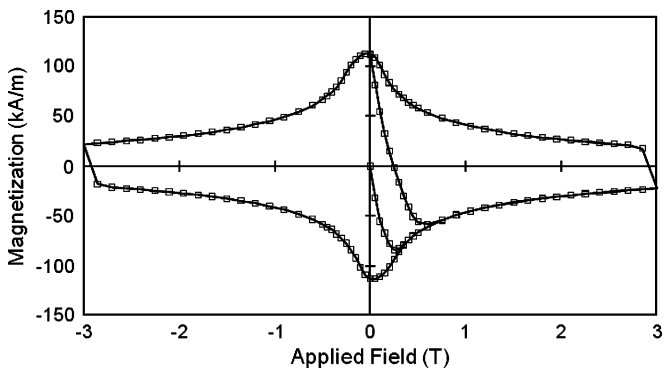


Fig. 9. Magnetization curve of strand T1791 with a subelement size of 16 μm.

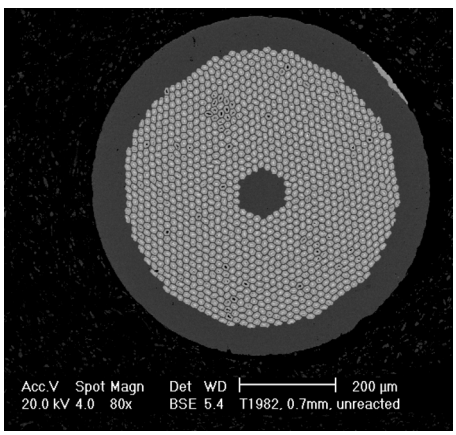


Fig. 10. Cross-section of strand T1982 at 0.7 mm, 1248 subelements.

AC-loss is half that of the 217-subelement wire (T1505), and is even close to the ITER specifications.

To further explore this tube-type strand, we increased the diameter of the tube used for the restack from 38.1 mm (1.5″) to 50.8 mm (2.0″), raised the subelement count to 1248, made a billet and drew it down to 0.7 mm. This billet is denoted as T1982. Fig. 10 shows the strand cross-section at 0.7 mm diameter, and its subelement size is about 12 μm. Results of measurement on this strand will be published elsewhere.

IV. Summary

We have continued to develop the simple tube-approach process to make Nb_3Sn strands with high subelement count. We made a standard strand with 192 Nb_3Sn subelements, with non-Cu values of J_c above 2500 A/mm^2 at 12 T and 4.2 K. This strand has a subelement size of 36 μm and its intrinsic irreversible strain limit is about 0.25%. To further improve this tube-approach process, we raised the subelement count to 744 and 1248 where the final subelement size is 16 μm and 12 μm in 0.7 mm strands, respectively. The 744-subelement strand has a non-Cu J_c (not yet optimized) of about 2000 A/mm^2 at 12 T and 4.2 K. This strand has a relatively high intrinsic irreversible strain limit of 0.45%, which is probably the highest amongst the Internal-Tin Nb_3Sn wires, and has relatively low AC loss which is about 1200 mJ/cm^3 for a $\pm$3 T field cycle.

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