Properties of Multifilamentary Nb₃Sn Superconductors
Fabricated by the Internal Bronze Approach

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Introduction

After the discovery\(^1\) that \(\text{Nb}_3\text{Sn}\) could be fabricated by reacting \(\text{Nb}\) with \(\text{Sn}\) provided by a bronze matrix, a number of different multifilamentary configurations were proposed. One configuration, which we designate as the internal bronze approach, consists of \(\text{Nb}\) tubes with bronze cores in a copper matrix. This configuration has several potential advantages over the external bronze approach,\(^1\) namely the \(\text{Nb}\) tubes serve as diffusion barriers so that another element such as \(\text{Ta}\) is not necessary to prevent \(\text{Sn}\) from contaminating the \(\text{Cu}\), and each superconductor element is surrounded by a high conductivity \(\text{Cu}\) matrix so that current transfer lengths are much shorter than in the external bronze case.\(^2\)

Initial results\(^3,4\) showed that the approach was amenable to conventional metal working practice and produced \(\text{Nb}_3\text{Sn}\) with good superconducting properties. In this paper we describe the results of experiments designed to optimize the critical current and to eliminate some manufacturing problems associated with the internal bronze approach. In addition, conductors of large cross sections (7.6 mm \(\times\) 7.6 mm) were prepared so that the internal bronze approach could be compared with the external bronze as a method for producing superconductors for mirror fusion applications.
Conductor Fabrication

A series of samples were fabricated from Nb tubes which were loaded with Cu 13 weight percent Sn cores. Extrusion billets 51 mm in diameter were prepared by stacking 37 tubes in a copper matrix; these billets were extruded with a typical area reduction factor of 23. After subsequent cold drawing and hexing operations, various numbers of these first stage extrusion rods were again loaded into copper cans and extruded. A series of samples were produced with the same overall dimensions (1.7 mm x 5.1 mm), but with varying numbers and size of filaments (Table I). These samples were used to study the effects of filament size and reaction temperature on the Nb$_3$Sn critical currents.

The production of large cross-section superconductors in long lengths for mirror fusion applications requires scale-up to large extrusion billets. Consequently, a 203 mm diameter billet containing 241 Nb tubes was extruded. Part of this material was drawn to produce 0.7 mm diameter strands (Table I) which were subsequently fabricated into a seven-strand cable. The remainder was loaded into a second 203 mm diameter billet and extruded to yield a 58,081 filament conductor. The Nb tubes after extrusion exhibited non-uniform cross sections and resulted in many breaks in the tube walls at final size. The behavior of this second-stage billet is attributed to either the large extrusion reduction (a factor of 64 reduction in area) or to the higher strength of the Nb after cold reduction prior to loading into the second-stage billet. Similar difficulty at lower extrusion ratios was experienced earlier with Nb 1 per cent Zr tubes, which have a higher work-hardening rate than pure Nb. These difficulties demonstrate that process scale-up to large billets is likely to introduce unexpected problems in any of the bronze/Nb approaches for fabricating Nb$_3$Sn.
Another practical problem associated with the internal bronze approach has been the difficulty of obtaining Nb tube of the desired size and wall thickness. One solution is to build up tubes by wrapping Nb sheet around a bronze core. In this manner, any combination of tube size and wall thickness can be obtained from Nb sheet which is readily available. A series of samples were prepared by wrapping multiple layers of 0.38 mm thick Nb sheet around a 102 mm diameter Cu 13 weight percent Sn rod and extruding in a 140 mm diameter Cu can. A 51 mm diameter billet containing 175 of these rods was extruded and fabricated into hexagonal cross-section rods for subsequent re-extrusion. A cross section of the Nb tube wall at this stage is shown in Figure 1; there are no indications that the tube wall is made up of 30 layers of Nb sheet.

Another 51 mm diameter billet was assembled from the first extrusion product and extruded to produce a 30,625 filament conductor. Part of this material was cold drawn and squared to produce a 7.6 mm x 7.6 mm cross-section conductor for evaluation (Figure 2). The remainder was reduced to smaller cross sections in order to evaluate the effect of tube size on current density. The parameters of this conductor are listed in Table II.

Results and Discussion

A series of samples were heat treated at 650, 700, and 750° C for various times and critical current as a function of applied field was measured. The effect of heat treatment time at 650° C is shown in Figure 3. The optimum time at 650° C is 100 to 120 hours; at 700° C the optimum is 80 to 100 hours; and at 750° C the optimum is 30 to 36 hours. The heat-treatment temperature which yields the highest critical current is 750° C for these internal bronze superconductors. This temperature is somewhat higher than the optimum identified for the
external bronze conductors (700 to 725°C) and may be related to the different strains produced in the Nb₃Sn layers resulting from the different fabrication routes.⁵

Critical currents were measured on the series of samples with varying filament (i.e. tube) sizes and the results for the 36 hour, 750°C heat treatment are shown in Figure 4. The critical current increased as the filament size decreased, and the highest critical current values were achieved at 17 μm (this agrees with earlier results⁶ which showed maximum critical current at a size of 13 μm). These results indicate that with the internal bronze as with the external bronze the optimum filament size is one as small as is consistent with reliable and economical manufacturing practice.

The data obtained for the samples prepared from wrapped Nb sheet are shown in Figure 4, and the microstructure of these samples are shown in Figure 2. The Nb₃Sn layer growth is uniform and comparable in thickness to that produced with Nb tubes for equivalent reaction conditions. Also, the critical current is comparable for tube and sheet Nb samples at comparable filament sizes. Hence, these results demonstrate that the wrapped Nb sheet approach is an acceptable route for fabricating Nb₃Sn superconductors.

The highest critical current densities in the Nb₃Sn layer obtained by the internal bronze approach are about 9 x 10⁴ A/cm² (H = 12 T) compared with about 2.5 x 10⁶ A/cm² (H = 12 T) for the external bronze approach.⁷ We believe this lower critical current value is due to the higher strains produced in the Nb₃Sn layer in the internal bronze configuration; this effect is explored in more detail in another paper in these proceedings.⁵ Some corroborating data on this effect, obtained on these internal bronze samples by K. Aihara and M. Suenaqa,⁸
are shown in Table III. For a comparable bronze to Nb ratio, the transition temperature depression in the internal bronze conductor is about 1.8 K, compared with about 0.2 K for an external bronze conductor. Similarly, if we plot the transition temperature reduction for the internal bronze sample in a master plot of $T_c$ reduction versus strain, this plot would indicate a strain of greater than one percent in the $\text{Nb}_3\text{Sn}$ layer.

Summary

1. The manufacturing difficulties associated with using Nb tubes in the internal bronze approach can be overcome by using wrapped Nb sheet to replace the Nb tubes.

2. The internal bronze approach can be utilized to fabricate superconductors with large cross section and moderate overall current densities ($7.5 \times 10^3$ A/cm$^2$ in the Nb + $\text{Nb}_3\text{Sn}$ + bronze at 12 T). However, additional work must be done to establish the parameters necessary for the successful extrusion of large (203 mm) billets.

3. The strains produced in the $\text{Nb}_3\text{Sn}$ in the internal bronze approach reduces the critical current by a factor of 3 - 10 in comparison to that achieved in the external bronze case.
Acknowledgments

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References


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Table I. Parameters of Samples Prepared from Nb Tubes

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Number of Filaments</th>
<th>Filament (Tube) Diameter (µm)</th>
<th>Conductor Size (mm)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>703</td>
<td>55</td>
<td>1.7 x 5.1</td>
</tr>
<tr>
<td>2</td>
<td>1,147</td>
<td>42</td>
<td>1.7 x 5.1</td>
</tr>
<tr>
<td>3</td>
<td>1,369</td>
<td>38</td>
<td>1.7 x 5.1</td>
</tr>
<tr>
<td>4</td>
<td>2,257</td>
<td>26</td>
<td>1.7 x 5.1</td>
</tr>
<tr>
<td>5</td>
<td>241</td>
<td>17</td>
<td>0.7 (Diameter)</td>
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</table>

Table II. Parameters of Samples Prepared from Wrapped Nb Sheet

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Number of Filaments</th>
<th>Filament (Tube) Filaments</th>
<th>Conductor Diameter (µm)</th>
<th>Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>30,625</td>
<td>34</td>
<td>7.6 x 7.6</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>30,625</td>
<td>17</td>
<td>4.3 (Diameter)</td>
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</table>
Table III. Transition Temperature (K) of Nb₃Sn Fabricated by the Internal Bronze Approach (Measured Inductively)

<table>
<thead>
<tr>
<th>Condition</th>
<th>$T_c$ (Midpoint)</th>
<th>$T_c$ (Onset)</th>
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</thead>
<tbody>
<tr>
<td>As Fabricated</td>
<td>16.20</td>
<td>17.35</td>
</tr>
<tr>
<td>With Cu Matrix Removed</td>
<td>16.50</td>
<td>--</td>
</tr>
<tr>
<td>With Bronze Core Removed</td>
<td>17.97</td>
<td>18.10</td>
</tr>
</tbody>
</table>
Figure Captions

Figure 1. Transverse section of Nb tube walls (darkest phase) after extrusion and cold drawing. The individual wrapped Nb sheets are no longer distinguishable.

Figure 2.a Cross section of 30,625 filament conductor produced from wrapped Nb sheets.
   b One group of 175 Nb tubes from the 30,625 filament conductor, which shows good wall integrity and reasonably uniform wall thickness.

Figure 3. Critical current as a function of heat treatment time at 650° C for sample number 5.

Figure 4. Critical current as a function of filament diameter for samples reacted at 750° C. Critical current increases as filament size decreases.
Figure 2

(a) 7.6 mm

(b) 0.2 mm
Heat treatment temperature = 650°C

Figure 3
Figure 4