Superconducting Wire with Small Filaments for SSC Magnets

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In order to achieve the highest field performance for SSC magnets, superconducting wires with small filaments have been required. Superconducting wires with filament size of 1-3 microns having excellent critical current densities have been already developed. For instance, a NbTi alloy superconducting wire with a filament size of about five micron achieved $J_c=2.8 \times 10^5$ A/cm$^2$ at 5T and 4.2K. A Nb3Sn compound superconducting wire with a filament size of about one micron also performed $J_c=2.3 \times 10^5$ A/cm$^2$ at 8T.

This paper attempts to clarify and propose standard Nb-50 wt% Ti alloy and multifilamentary bronze Nb3Sn configurations of interest to SSC magnet designers.

Introduction

A magnet development for the proposed 20 TeV on 20 TeV Superconducting Super Collider (SSC) depends significantly on developments in superconductor technology. In particular, the field quality problems are more serious for the SSC with the reduced aperture than for the Fermilab Tevatron. In these dipole magnets, field errors are generated by conductor misplacement and the effects of persistent currents at injection field levels. Although the correction due to the misplacement of the coil edge is actually achieved in practice, under certain conditions the coil can exhibit a sextupole moment even if the fabrication of the magnet were done to perfection. It is the effects of persistent current due to the penetration of shielding current into the superconducting filaments that is the obvious way to limit the persistent current fields to a negligible level is to reduce the filament size. But there are technical problems of manufacturing the superconducting wires with small filaments below 5 or 6 micron and high critical current densities. Further a choice of materials and conductor configurations must be based on mechanical properties, ease in winding, reliability and cost.

Nb-50 wt% Ti Alloy Wires

Fabrication

Generally it has been believed that the good superconducting properties of Nb-Ti composites are obtained by the process of intermediate heat treatment and heavy cold working. Further in order to achieve high critical current densities it has been emphasized that chemical homogeneity of Nb-Ti ingots or initial rods is important. In particular, the homogeneity of Nb-Ti ingot will be required to obtain sound small filaments.

Furukawa has well established the fabrication process for Nb-Ti wires with small filaments. For instance, a shape of the small filament is shown in Fig.1.

Critical Current Densities

Updated data on the Nb-50wt% Ti alloy wire having various filament diameters manufactured by Furukawa are shown in Fig.3. Critical current density results are reported at a sensitivity of 10-12ncm for only Nb-Ti alloy. The wire had the Cu/NbTi ratio of one to two, which was determined by etching and weighing, and was fabricated by a single stacking technique.

It is found that critical current densities in fields both 5T and 8T and at 4.2K exhibit the prominent values for the filament size of around 50 micron and tend to decrease gradually with decreasing the filament size. The best values of critical current densities at 5T and 4.2K for 9 micron filament and 5 micron filament were $3 \times 10^5$ A/cm$^2$ and $2.8 \times 10^5$ A/cm$^2$.
A/cm², respectively. It is also found that the binary Nb-Ti alloy exhibits excellent critical current densities even if the filament size was reduced to around one micron. Although these data are not always optimized, they are more excellent than that of a previously reported sample of 1.35 x 105 A/cm² at 5T for filaments of 1.3µm diameter. They overcome a design point in the critical current density of 2.4 x 105 A/cm² at 5T below the filament size of 5 or 6 micron, and thus they are well enough to be used for the design of the SSC magnets.

It is predicted that in order to limit the persistent current field to negligible level a filament size of two to three micron might be sufficient. Since each strand has the diameter of about 0.7 mm and the Cu/SC ratio of 1.3 to 2 in the SSC Reference Design, this would require more than 20,000 filaments. Consequently to get more than about 10,000 filaments will require a manufacturing technique known as double stacking. Even though the double stacking technique is adopted, there will be no technically serious problems or no significant degradations in critical current density.

Choice of Ti-Content

A comparison with critical current densities as a function of magnetic fields for typical Nb-Ti alloy wires is shown in Fig.4. The wires reported here are given in Table 1. It can be seen that the critical current densities of F50 Ti below 8T are better than those of others.3 This result gives support to the previous report, that is, the higher Ti-content alloy exhibited good superconducting properties due to the combination of a fine sub-band structure and Ti precipitates.4

Assuming the SSC machine operated at 4.2K and below 8T as the maximum field, a choice of the Nb-50wt% Ti might be better. Marked advantages of Nb-50wt% Ti are its lower material cost and higher reliability for fabricating wires with small filaments.

<table>
<thead>
<tr>
<th>Ti-cont.</th>
<th>Wire dia.</th>
<th>No.of Cu/NbTi Filament</th>
<th>diam. µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>F50 Ti</td>
<td>0.75</td>
<td>2.410</td>
<td>0.65</td>
</tr>
<tr>
<td>F46.5 Ti</td>
<td>0.77</td>
<td>2.300</td>
<td>2.00</td>
</tr>
<tr>
<td>UN46.5 Ti</td>
<td>0.805</td>
<td>5.95</td>
<td>1.35</td>
</tr>
</tbody>
</table>

![Critical Current Densities](Fig.4)

Critical Current Densities

Critical current densities on the bronze processed Nb3Sn wires having various filament diameters are summarized in Fig.6. The wires reported here are given in Table 2. Critical current density results were obtained at a sensitivity of 10-11A/cm² and at 4.2K. It is found that the filament size to obtain the good properties becomes around one micron and the Jc degradation occurs rapidly with decreasing the filament size. As shown in the figure, the highest value is 2.3 x 10^5 A/cm² at 8T which is about twice higher than the Nb-Ti alloy wires shown in Fig.4.

It is also found that the bronze-processed Nb3Sn wire is promising for high-energy accelerators required a higher magnetic field and a higher critical current density.

It is interesting to note that the critical current densities of the wire with sub-micron filaments are rapidly decreased. A number of factors can influence the values of critical current densities at intermediate magnetic fields, such as filament uniformity, grain sizes of Nb3Sn, change in pinning mechanism, current sharing among filaments and compositional variations from filament to filament.5 Although it is difficult to clarify a reason of them, it is suggested that the filament uniformity will be one of significant factors.

Bronze-Process Nb3Sn Compound Wires

Fabrication

The so-called "bronze process" for fabrication of multifilamentary Nb3Sn wires and its modifications have been developed and successfully made for various applications. In particular, multifilamentary Nb3Sn wires incorporating Ti are now being commercially produced.

The multifilamentary composite was fabricated in three stacking stages with intermediate annealing and cold drawing stages.6 The first stage consisted of a pure Nb rod in a bronze pipe of Cu-14.3wt% Sn-0.2wt% Ti alloy. After working, these composite rods were inserted into a second billet, extruded and drawn. The final extrusion billet consisted of the second composites and a Nb diffusion barrier and a copper stabilizer. This extrusion was drawn, twisted and insulated. This composite wire will be typically formed into a compacted-stranded wire before reaction heat treatment as shown in Fig.5. It is also feasible to form the wire from an array of subcables. Reaction of these composites to form the compound superconductor Nb3Sn was performed at 550-700°C for several days in an inert atmosphere.

In order to achieve small filaments and high critical current densities, there are two technical aspects. One is that nonuniformity of the filaments have to be minimized. Because the so-called "sausaging" for unreacted Nb filaments causes the cross-sectional area to fluctuate and then diffusion reaction to be uncontrollable. The second aspect is that the grain size of Nb3Sn has to be minimized. For example, an optimized Nb3Sn wire exhibited uniformity of the filaments and a small grain size of about 0.1 µm.

![Fig.5](Fig.5)
Table 2 Description of the wires

<table>
<thead>
<tr>
<th>No. of filaments</th>
<th>Copper stabilizer (%)</th>
<th>Bronze/Barrier (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FN-2</td>
<td>21.4</td>
<td>Nb(5.26)</td>
</tr>
<tr>
<td>FN-2K</td>
<td>43.1</td>
<td>Nb(6.32)</td>
</tr>
</tbody>
</table>

Fig. 5 Overall \( J_c \) versus filament size of Nb3Sn superconducting wires

Comparison with Internal Tin Process

An overview of the critical current densities of Nb3Sn wires is shown in Fig. 7. The wires reported here have the same filament size of one micron. But the reported \( J_c \) for an internal tin process was based on the central bronze region only (not including copper stabilizer and barrier), measured at a resistivity of \( 1 \times 10^{-12} \text{ohm} \cdot \text{cm} \). It can be seen that the bronze process when compared to the internal tin process exhibits superior performance as measured by current density. For example, the critical current density at 8T for the bronze process is \( 2.3 \times 10^5 \text{A/cm}^2 \), which corresponds with a value of 1.5 times for the internal tin process.

As a result of the comparison there are following merits of the bronze-process conductor: the wire with small and uniform filaments of one micron is fabricated by the conventional process, the persistent current fields is reduced enough and reliability in conductor fabrication combined with fabricating large Nb3Sn coils is superior on many experiences.

Conclusions and Recommendations

1. Superconducting critical current densities \( J_c \) of Nb-50 wt% Ti wires in fields up to 8T and at 4.2K are superior to those of Nb 46.5 wt% Ti wires and pertinent for the SSC magnets.
2. The best value of \( J_c \) for Nb-50 wt% Ti wire and 5 micron filaments is \( 2.8 \times 10^5 \text{A/cm}^2 \) at 5T and 4.2K.
3. The bronze-processed Nb3Sn wire exhibits superior performance when compared to the internally tin-processed wire.
4. The best values of \( J_c \) for bronze-processed Nb3Sn wires at 8T and 12T are \( 2.3 \) and \( 1 \times 10^5 \text{A/cm}^2 \), respectively.

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References

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