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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 Jc~2.8 x 105 A/cm2 at 5T and 4.2K. A Nb3Sn compound superconducting wire with a filament size of about one micron also performed Jc~2.3 x 105 A/cm2 at 8T and 4.2K.

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

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 placement error 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.[1]

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-50wt% Ti Alloy Wires

Fabrication

Generally it has been believed that the good superconducting properties of Nb-Ti composites are obtained by the processing of intermediate heat treatment and heavy cold working.[2] 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.[3] In particular, the homogeneity ingot will be require to obtain sound small filaments.

Furukawa has well estabished the fabrication process for Nb-Ti wires with small filaments.[4] For instance, a shape of the small filament is shown in Fig.1.

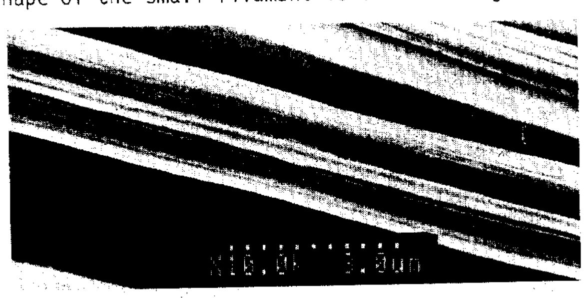

Fig.1 A SEM photograph of 1.5 μm dia. Nb-50wt%Ti filaments

There are no sausagings, no intermetallics and extended structures ran parallel to the filament axis.

The Nb-Ti rods homogenized and worked were inserted into copper tubes, and the composite was reduced to a desired size and shape. The composites were then packed into a extrusion can. The composite was reduced to a diameter of about 50 mm by extrusion at around 600°c. The extruded composite was reduced to a final wire diameter by cold drawing and intermediate heat treatment, and the composites were formed to the compacted-stranded shape as shown in Fig.2. Of course the ratio of copper to Nb-Ti was controlled during the abovementioned processes.

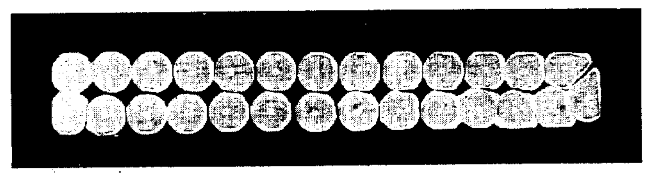

Fig.2 A compacted-stranded wire of 27-strand

The compacted-stranded wires with intermediate filament size of 6 to 10 micron have been supplied to Fermi Nationl Laboratory for Energy Saver/Tevatron KEK in Japan for TRISTAN Project and DESY in Federal Republic Germany for HERA Project.[5]

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 10-12Ωcm 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 ten 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 x 105 A/cm2 and 2.8 x 105

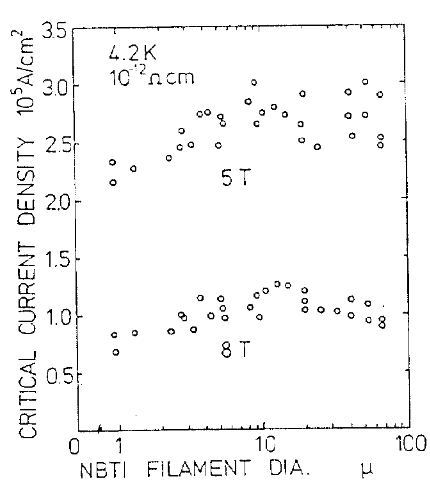

Fig.3 Effect of filament size on Jc versus magnetic field

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 1.95 x 105 A/cm2 at 5T for filaments of 1.3μm diameter.[6] 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 α-Ti precipitates.[7]

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 1 Specification of the wires

	Ti-cont. wt%	Wire dia. mm	No.of filaments	Cu/NbTi ratio	Filament dia. μm
F50 Ti	50	0.75	2,410	1.65	9.1
F46.5 Ti	46.5	0.77	2,300	2.00	9.3
UW46.5 Ti[3]	46.5	0.805	535	1.35	23

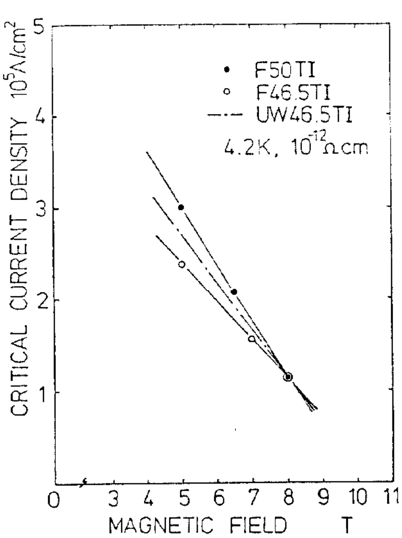

Fig.4. Critical current densities for wires 50wt% Ti and 46.5wt% Ti as a function of magnetic field at 4.2K

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.[3] The first stage consisted of a pure Nb rod in a bronze pipe of Cu-14.3wt% Sn-0.2 wt% 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 opitimized Nb3Sn wire exhibited uniformity of the filaments and a small grain size of about 0.1 μm.

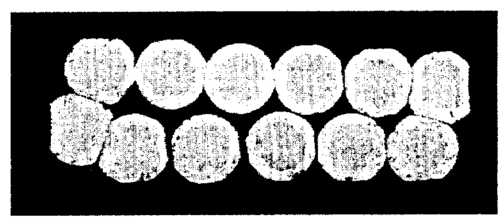

Fig.5 A compacted-stranded wire of bronze-processed Nb3Sn

Critical Current Densities

Critical current densities on the bronze-processed Nb3Sn wires having various filament diameters are summerized in Fig.6. The wires reported here are given in Table 2. Critical current density results were obtained at a sensitivity of 10-11Ωcm and at 4.2K. It is found that the filament size to obtain the good properties becomes around one micron and the Jc degradation occures rapidly with decreasing the filament size. As shown in the figure, the highest value is 2.3 x 105 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 intrmediate 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.[9] Although it is difficult to clarify a reason of them, it is suggested that the filament uniformity will be one of significant factors.

Table 2 Description of the wires

	Cu %	Barrier(%)	Bronze/ filament	No. of filaments
FN-2	21.4	Nb(5.26)	3.7	2,016
FN-2K	43.1	Nb(6.32)	4.1	7,225

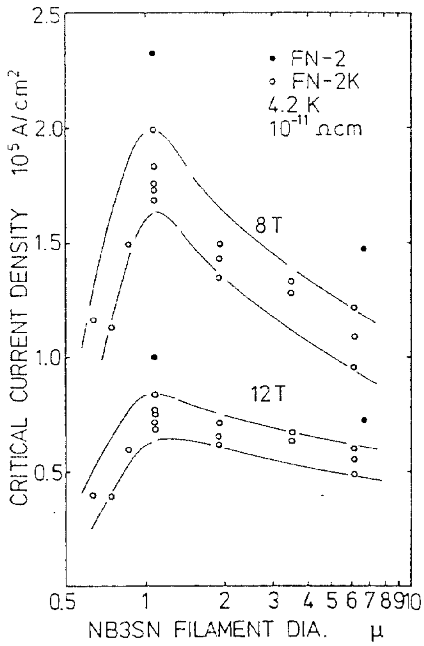

Fig.6 Overall Jc versus filament size of Nb3Sn superconducting wires

Comparison with Interanl Tin Process

An overiview 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 Jc 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 x 10-12Ωcm.[10] 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 x 105 A/cm2, 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 well enough and reliability in conductor fabrication combined with fabricating large Nb3Sn coils is superior on many experiences.

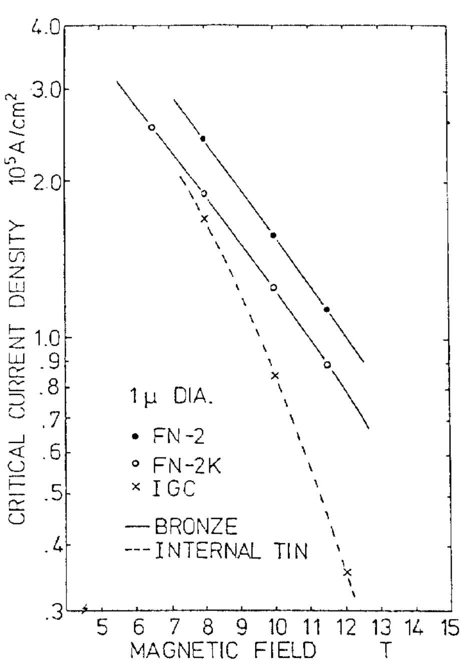

Fig.7 A comparison with bronze process Nb3Sn and intranl tin process Nb3Sn

Conclusions and Recommendations

1. Superconducting critical current densities Jc of Nb-50wt% Ti wires in fields up to 8T and at 4.2K are superior to those of Nb-46.5wt% Ti wires and pertinent for the SSC magnets.
2. The best value of Jc for Nb-50wt% Ti wire and 5 micron filaments is 2.8 x 105 A/cm2 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 Jc for bronze-processed Nb3Sn wires at 8T and 12T are 2.3 and 1 x 105 A/cm2, respectively.'

Acknowledgments

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References

1. H. E. Fisk et al., "SSC Magnetic Field Quality Considerations", to be submitted to Proceedings of 1984 Summer Study on the Design and Utilzation of the SSC, Snowmass(1984)
2. A. W. West et al., "Microstructural Changes Produced in a Multifilamentary Nb-Ti Composite by Cold Work and Heat Treatment", Metall. Trans. A, vol. 15A(1984) 843
3. D. C. Larbalestier et al., "High Critical Current Densities in Industrial Scale Composite Made from High Homogeneity Nb 46.5 Ti", to be submitted IEEE Trans. on Magn. vol. MAG-21(1984)
4. Y. Tanaka et al., "Recent Activites on High-Field Superconductors at Furukawa", 3rd US-Japan Workshop on High Field Superconducting Material for Fusion, Tsukuba, Japan(1984)
5. Y. Furuto,"An Overview of Practical Superconductor Development in Japan", Advance in Cryogenic Engineering, vol. 30(1984) 721
6. P. Dubois et al., "NbTi Wire with Ultra-Fine Filaments for AC Use", to be submitted to IEEE Trans. on Magn. vol. MAG-21(1984)
7. I. Pfeiffer et al., Acta Metall., vol. 16(1968) 1429
8. R. M. Scanlan et al., "Fabrication and Evaluation of a Cryostable Nb3Sn Superconductor for the Mirror Fusion Test Facility (MFTF-B)", to be submitted to IEEE Trans. on Magn. vol. MAG-21(1984)
9. M. Suenaga et al., "Superconducting Critical-Current Densities of Commercial Multifilamentary Nb3Sn (Ti) Wires made by the Bronze Process", Cryogenics vol.25(1985) 123
10. B. A. Zeitlin et al., "An Oveview of the IGC Interanl Tin Nb3Sn Conductor", 3rd US-Japan Workshop on High Field Superconducting Materials for Fusion, Tsukuba, Japan(1984)